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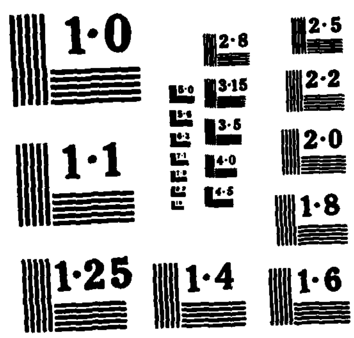

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June 1985

Final Report

PHYSICAL DISTRIBUTION SYSTEM FOR AIRCRAFT EXTERNAL FUEL TANKS—SURVEY

Contract No. N00600-82-D-8362 D.O. 0003
Report Period: 1 March 1985 to 31 May 1985

By: GERRY B. ANDEEN, ROY D. KORNBLUH, THOMAS P. LOW, RICHARD H. MONAHAN, WILLIAM PARK, ANNE W. PETERSON

Prepared for:

DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER
BETHESDA, MARYLAND 20084

REPORT No. CMLD-CR-47-85

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The general objective of this study was to conduct a survey and analysis of current and planned aircraft external fuel tanks, with emphasis on the disposability and nestability aspects of these fuel tanks. The study focused on design requirements, fabrication and assembly, and physical distribution, with particular attention directed to the use of robotic equipment for the assembly of nestable fuel tanks aboard ship. The principal conclusion of the study is that the development of disposable, nestable external aircraft fuel tanks with automated assembly aboard ship, using robotic equipment, is a feasible option for implementation within the next five to ten years.

Chapter I of the report presents an introduction and summary of the major results of the survey. Chapter II then provides a summary description of the tentative operational requirements established by the Navy for disposable, nestable external aircraft fuel tanks.

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Chapter III presents a discussion of the possible fabrication and assembly techniques and problems for such fuel tanks. Chapter IV then discusses the physical distribution aspects of external aircraft fuel tanks. Chapter V concludes with a listing of the conclusions and recommendations resulting from this analysis.

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PREFACE

This report documents the analysis and findings of a research project conducted for the David W. Taylor Naval Ship Research and Development Center (DTNSRDC), Bethesda, Maryland. The technical monitor was M.J. Zubkoff, Code 187, of DTNSRDC. The research was sponsored by the Naval Air Systems Command under the direction of D.S. Hurst, Code AIR-310I. The work was performed under Contract N00600-82-D-8362 D.O. 0003.

The research was performed within the following three organizational activities at SRI International:

- Systems Evaluation Center (SEC) of the Research and Analysis Division (RAD). L.L. Gilbert is Director of SEC, and D.D. Elliott is Vice President of RAD.

- Engineering Sciences Laboratory (ESL) of the Advanced Technology Division (ATD). F.J. Kamphoefner is Director of ESL, and W.F. Greenman is Vice President of ATD.

- Robotics Laboratory (RL) of the Advanced Technology Division (ATD). D. Nitzan is Director of RL, and W.F. Greenman is Vice President of ATD.

R.H. Monahan of SEC was program manager and co-principal investigator. The other principal investigators were G.B. Andeen, R.K. Kornbluh, and T.P. Low of ESL, and W.T. Park of RL. A.W. Peterson and D.L. McPherrin of SEC provided additional support for this project.

I INTRODUCTION AND SUMMARY

A. Introduction

A need has arisen in the Navy community for research and development on aircraft external fuel tank adequacy in the fleet, specifically within the areas of:

- Storage location
- Methods for distribution
- System responsiveness to need
- Alternatives for acquisition.

There is substantial concern about the adequacy of the present system to supply and support operational needs for external fuel tanks. Inadequate responsive access to such fuel tanks will have a deliterious effect on the operational readiness of fleet aircraft, and consequently, on carrier battle group readiness.

As a first step in the research and development plan for the distribution of aircraft external fuel tanks, a survey was conducted. The survey covered current, on-going, and planned movement, storage, fabrication, and inventory of aircraft external fuel tanks. This survey included literature searches of the Defense Technical Information Center (DTIC) library, the Defense Logistics Studies Information Exchange Library (DELSIE), and the NASA RECON File D, which includes a number of abstract sources such as Scientific and Technical Aerospace Reports (STAR), and International Aerospace Abstracts (IAA). From these searches, 52 documents and articles were identified and ordered that related to aircraft fuel tanks. At the writing of this report, 46 of these documents were received and reviewed. Besides reviewing the literature searches, project personnel visited three Naval

activities (U.S. Naval Postgraduate School, Lemoore Naval Air Station, and Headquarters, Naval Air Systems Command) to discuss the external fuel tank problem with knowledgeable personnel. Additional telephone contacts were made with personnel at the U.S. Air Force Logistics Command, several U.S. aircraft companies, and suppliers of materials for fabrication of the tanks. Table 1 lists the various contacts that were made during this survey. The documents received from the literature search are included in the references appearing at the end of this report.

The next section summarizes results of the information gleaned from the sources above. Chapter II then provides a summary description of the tentative operational requirements established by the Navy for disposable, nestable external aircraft fuel tanks. Chapter III presents a discussion of the possible fabrication and assembly techniques and problems for such fuel tanks. Chapter IV then discusses the physical distribution aspects of external aircraft fuel tanks. Chapter V concludes with a listing of the conclusions and recommendations resulting from this analysis.

B. Summary

1. Design Requirements

The development of a disposable, nestable external fuel tank for Navy Fighter attack aircraft should satisfy a number of design requirements that will enable the aircraft to maintain their tactical range and mission endurance, especially in periods of protracted combat. These requirements stipulate that the fuel tanks must be:

- Functional
  - provide from 200 to 400 gal/tank of auxiliary fuel
  - be compatible with the F/A-18, A-4, A-6, and A-7 aircraft, and possibly with the F-14 aircraft
  - be aerodynamically sound

Table 1

CONTACTS -- INFORMATIONAL CALLS AND VISITS

Name	Company and Location	Subject
Tony Diaz	Wright-Patterson AFB (OH) (Air Force Logistics Operations Center - AFLC/LOC)	Nestable Fuel Tanks
Jim Gilcrease	General Dynamics (Ft. Worth, TX)	Fluid Systems
Keith Presswood	General Dynamics	Fluid Systems
John Calagari	Grumman (Bethpage, NY)	Structural Design
Les Brower	Grumman	Structural Design
R.L. (Bob) Jung	McDonnell-Douglas (St. Louis, MO)	Fuel Tank Repair
Heinz Gerhardt	Northrop (Hawthorne, CA)	Fuel Systems, Propulsion Research
Dick Hartley	Northrop	F-18 Technology
Irving Hirschhorn	Northrop	F-18 Aerosciences
Lt. Archibald McKinlay, VI	U.S. Naval Postgraduate School, Aeronautical Engineering Dept., Monterey, CA	Nestable, Disposable Fuel Tanks
Jerry Stultz	Naval Air Systems Command NAVAIR 05-303, Arlington, VA	External Fuel Tanks
Commander Roger Hill	Light Attack Wing Pacific Fleet Lemoore Naval Air Station, CA	External Fuel Tanks

Table 1 (Concluded)

Name	Company and Location	Subject
Lt. R.M. Styczynski	Light Attack Wing Pacific Fleet Lemoore Naval Air Station, CA	External Fuel Tanks
L.J. Bement	NASA Langley Research Center Hampton, VA	Explosive Seam Welding
J.P. Dark	Bionic Arm & Robotics, Inc. Jackson, MI	Manipulator for Lifting Heavy Objects
Dr. R. Froberg	Pfizer Materials, Pigments and Metals Division Easton, PA	Fire Protection Materials
D.L. Hall	Fiber Materials, Inc. Biddeford, ME	Fire Protection Materials
John Nygard	3M Corp St. Paul, MN	Scotchweld Structural Adhesive
J.A. McNickle	Loctite Corp. Newington, CN	Sealant Dispensing Systems

- weigh not more than 275 pounds when empty
- withstand the stresses of a catapult launch and subsonic climb, cruise, and limited maneuvering

- Durable
  - maintain structural integrity over the wide ranges of temperature, humidity, and precipitation encountered at sea.
- Disposable
  - be jettisonable when empty or partially full
  - be available in large quantities aboard ship
  - be produced at low cost (less than $10,000)
- Storable
  - possess higher storage density than present tanks
  - have capability of being rapidly assembled aboard ship (goal is one every 6 minutes)
- Safe
  - radiate no toxic fumes
  - be rupture-proof, shatter-proof, and non-flammable
  - withstand high fuel afterburner temperatures

2. Fabrication and Assembly

a. Fabrication of Nestable Elements

There are five major factors to consider in the fabrication of the elements of a disposable external aircraft fuel tank: materials, joining mechanisms, geometry, internal/external plumbing, and inspection.

1) Materials.

The principal materials suggested for use in the fabrication of nestable fuel tanks are as listed below, together with their relevant properties:

- Steels
  - poor strength-to-weight properties
  - poor corrosion resistance
- Aluminum
  - good strength-to-weight properties
  - good corrosion resistance
  - poor fire resistance (can be improved through use of fire-resistant coatings - ablative or intumescent compounds.)
- Titanium
  - good strength-to-weight properties
  - good corrosion resistance
  - good fire resistance
  - requires special welding techniques
  - extremely expensive
- Plastics
  - acceptable strength-to-weight properties but require thick walls
  - poor fire resistance
- Composites
  - excellent strength-to-weight properties
  - good fire resistance
  - good corrosion resistance
  - expensive, especially in nestable configuration

2) Joining Mechanisms

The procedures for joining the section of nestable fuel tanks must possess the strength to withstand the stresses transmitted during a catapult launch and under limited subsonic maneuvering. An analysis was performed to estimate the required joint strength. This analysis considered a common configuration with a short cylindrical midsection, a semi-ellipsoidal nose cone of circular cross-section and a conical

tail section. The calculations were performed for 1g loadings, but can be extrapolated to other loadings since the relationship is linear. Figures 1 and 2, presented in Section III.A.2, summarize the results of this analysis. For a nestable fuel tank similar to the present AERO1D tank, the peak hoop stresses attained during a catapult launch would be about 1110 lb per inch of seam length at the nose joint and 3150 lb per inch of seam length at the tail joint.

During this survey, several possible joining and sealant procedures were identified. These procedures and some of their relevant properties are as follows:

- Lap Joints Using Adhesives
  - are strong enough to withstand sheer stresses transmitted during a catapult launch
  - can withstand high temperatures from a jet blast
  - have excellent sealing properties

- Composite Winding
  - may be susceptible to fuel corrosion (additional sealant protection would be required)
  - may exceed assembly time limitations
  - may produce harmful fumes

- Circumferential Clamps
  - used with longitudinal half shells
  - have O-rings that provide sealing

- Mechanical Fasteners (bolts, rivets, etc.)
  - require sealants
  - have many small parts

- Welding of Metallic Tank Elements
  - is probably fillet weld on a tightly fitting lap or butt joint
  - is structurally sound

- requires automatic welding equipment to meet time limitations

- Explosive Welding
  - is simple, fast and reliable
  - releases no toxic fumes
  - reduces hazardous concerns through use of internal fuel tank explosion

- Bladders as Sealants
  - joints of tank still need to be structurally sound
  - bladders would have to be anchored to tank walls

- Mounting Plates (Strongbacks)
  - required by most designs to distribute stress at point of attachment
  - provide surface for ejection foot to strike
  - probably built into midsection structure during fabrication

3) Geometry

A main concern is to evaluate nestable schemes for high density storage of external aircraft fuel tanks. To evaluate alternative schemes, an overall packing factor (OPF) was established. This OPF is independent of the actual number of tanks to be nested. This factor is given as

$$\text{OPF} = \frac{\text{volume required to store one tank}}{\text{volume required to store an additional tank}}$$

When the storage volume of a single nestable tank is the same as that of an assembled tank, then the OPF is related to the more standard "nesting ratio" (NR) as follows, where N is the number of tanks to be nested:

$$\text{NR} = \frac{N}{(N-1)/(\text{OPF} + 1)}$$

The geometrical configurations proposed in the literature consist either of three axially-sliced sections, or two longitudinally-sliced sections.

Four principal alternatives were identified and are described as follows:

- Long Cylindrical Midsection with Sealed Ends, with Short Nose and Tail Sections (Figure 3, Section III.A.3)
  - assembly process simple
  - joints need not hold a large load or prevent fuel from leaking
  - midsection not nestable
  - OPF small (less than 2.0)

- Short Preassembled Cylindrical Midsection with Long Nose and Tail Sections (Figure 4, Section III.A.3)
  - joints must hold large structural load and seal in the fuel
  - midsection not nestable
  - OPF of 5.0 is a reasonable expectation

- Short Unassembled Cylindrical Midsection with Long Nose and Tail Sections (Figure 5, Section III.A.3)
  - joints must hold large structural load and seal in the fuel
  - midsection must be assembled and strongback attached onboard ship
  - midsection nestable
  - OPF of 15.0 is a possibility

- Two Horizontal "Canoe-like" Sections (Figure 6, Section III.A.3)
  - joint must hold large structural load and seal in the fuel
  - internal plumbing not preassembled

- strongback must be attached onboard ship
- all sections nestable
- OPF of 6.0 appears reasonable

4) Internal/External Plumbing

The fuel tanks would require two fluid ports and possibly no electrical connections. Pressurized air would be pumped through one port allowing fuel to be drawn into the main fuel tanks through the second port. The flow rate need only be regulated within a specified range and the amount of fuel in the tanks need not be known.

Composite tanks will require consideration of port locations at winding time so that doilies may be placed at the desired port locations to provide reinforcement for subsequent hole drilling.

Plumbing standardization for different types of aircraft may be accomplished through the use of adapter plates that mate the standardized ports to the variable port locations of the different aircraft.

5) Inspection

The elements of the nestable external fuel tanks must be fabricated properly for rapid assembly in a shipboard environment. Mating surface dimensions must match closely and be clean. Any protective fire coating applied at production time must not be damaged. Protective wrappings may be required to ensure these conditions.

Semi-automated test procedures for quality control of composite materials, adhesives, and sealants have been developed and may be useful in the production and field assembly of nestable fuel tanks.

b. Assembly of Fuel Tanks

There are six major factors to consider in the assembly of the nestable external aircraft fuel tanks aboard the aircraft carrier (or possibly a supply ship): robotic equipment, materials, personnel, maintenance, inspection, and aircraft interface.

1) Robotic Equipment

The assembly and testing of the fuel tank would take place in a specialized machine. This machine would hold the two parts to be joined, align them, and move them together as required. This machine must also be able to rotate either or both parts so that the forming or welding tool could reach the entire seam. An alternative would allow moving of the tool around the circumference of the tank parts. The machine would also have a head that mated to the tank support so that the tank could be pneumatically tested after fabrication. The assembly/testing machine would weigh about 1000 to 2000 pounds, and could be mounted between the tank part supply and the hangar deck.

Robotic equipment is better suited to some parts of the fuel tank assembly procedure than others. There are six steps in the procedure:

(1) Obtain a fore, aft, and center tank section.

(2) Prepare the shells for mating.

(3) Mate the shells (to each other or to a center section).

(4) Fasten the shells (together or to the center section).

(5) Test the assembled tank functionally.

(6) Deliver the finished tank.

The methods of storing, joining, testing, and delivering the shells must be carefully engineered to place the fewest demands on the automation equipment. Such engineering will lead to a more robust and reliable automatic system and will also make it easier for people to perform the task if the automation equipment is out of service.

Steps (1) and (2) are likely to be more difficult, because they present the robot with more variability than the other steps do, because:

- It may not be practical to produce a robot that can obtain fuel tank shells from casual storage areas. Insisting on using a mobile robot to fetch shells will only result in an inefficient, caged-off "robot run".

- It may not be practical for the robot to remove conventional packaging material from the fuel tank shells or shipping pallets.

Use of personnel and conventional material transport equipment would probably be more efficient and timely in the performance of these steps.

2) Materials

Materials would depend on (1) the tank material selected, and (2) the method of joining to be used.

3) Personnel

A tradeoff exists between equipment complexity and human involvement. The driving force will be the requirement for a rapid assembly time. Although automatic equipment operation is the desired plan, a man would still be needed to set up and initialize the equipment and then monitor its operating performance.

The assembled fuel tanks would be removed from the equipment manually and either taken to the aircraft for use or put in temporary storage. The crew that performs this task would be the same crew that maintains the aircraft.

4) Maintenance

The equipment would require maintenance similar to that for other electrical-mechanical systems. After each run, parts of the equipment may need cleaning to prevent plugging or similar failure.

5) Inspection and Testing

The main inspection would be the monitoring of the equipment behavior during assembly. Parts that resist sliding together, for example, suggest a rough-edge or other failure. Such a problem would be brought to the operator's attention. A complete and accurate automatic inspection is possible, but it would be much more cost effective to flag unusual behavior. Such flagging reduces equipment cost and allows the operator to take corrective action, possibly saving parts.

The main testing method would be done by pressurizing the tank to a rated pressure (86 psi) and then monitoring the holding of the pressure. This could be done automatically by the assembly/ testing machine.

6) Aircraft Interface

The tanks would be taken manually from the assembly area to the aircraft.

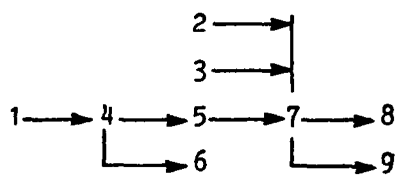
Different aircraft would require different attachment and plumbing details. This means that (at least) the central portion of the tank, the connection fittings, or an adapter must be individualized for each aircraft. Stowage and assembly planning would be needed if more than one kind of tank were being assembled for a mission.

c. Straw Man Design Concept

A straw man design concept was conceived for the tank assembly facility (Figures 7, 8, and 9, Section III.C). The faciity consists of the following stations:

(1) Tank end section pallet
(2) Tank center section pallet
(3) Assembly/test supply pallet
(4) Tank section de-stacking area
(5) Unstacked tank section area
(6) Separator ring disposal area
(7) Automatic assembly and testing machine
(8) Completed tank storage rack
(9) Defective tank storage rack.

Parts flow through the facility as follows:



d. General Comments on Design Concept

Material flow is approximately unidirectional through the facility. This reduces congestion at entry and exit points. Individual material flow paths do not cross and are primarily horizontal, with vertical access possible at all stations, along all paths. This allows use of commercially available gantry-style robot arms for improved lifting capacity for a given accuracy and/or cost.

Use of existing commercial equipment would be preferable to development of a new manipulator because existing equipment is cheaper, replacements would be easier to obtain, the manufacturer

could provide skilled service, and competition would result in future price/performance increases. Simple sensors (e.g., contact switches) would meet most of the sensing needs in this facility, except for the assembly/test station.

The facility will require one computer that communicates with the operator and coordinates the activities of the other computers and equipment. This computer could probably also operate the robot arms, but it may be safer to use a different computer. The robot(s) themselves may have multiple embedded microprocessors for joint servo and gripper control. The assembly/test station will need at least one computer of its own for real-time process control.

Interfaces between pieces of equipment should be designed for easy upgrading, expansion, and application to other shipboard activities. Equipment should be modular, and standards should be established for interconnection of modules. Existing industrial or naval standards should be adopted. Existing standards are preferred to newly defined standards.

3. Physical Distribution

The physical distribution of external fuel tanks for Navy fighter/attack aircraft complies with the standard procedures for the distribution of aviation peculiar items within the Navy supply system. The functions of physical distribution can be segregated under four major headings: inventory, movement, storage, and acquisition, which includes integrated logistics support (ILS).

a. Inventory

There are three levels of inventory for Naval aviation material: the organic level of supply and two echelons of resupply. The aircraft squadrons draw supplies from the organic level. As necessary, the organic level requisitions additional supplies from the

first echelon, which in turn, may requisition replenishment from the second echelon.

Materials stocked at the organic level are specified in an Aviation Consolidated Allowance List (AVCAL) or other specially tailored support allowances. These materials are carried onboard ship for sea-based squadrons or are kept at the shore station for shore-based squadrons. The AVCAL lists the components, repair parts, and consumable items required for a ship or shore activity to perform its operational mission supporting assigned aircraft, with consideration for available organic repair capability. Whenever special operations are anticipated, the AVCAL is either augmented or replaced by a special allowance list.

The first echelon of resupply for sea-based aircraft squadrons is usually the associated shore-based activity assigned under the base level concept. Fleet issue ships (either accompanying a task force or serving as members of the mobile logistic support force (MLSF)), do not normally carry aviation-peculiar material. However, in special deployments, these ships might carry this material, including external fuel tanks. In this case, the first echelon of resupply would be the fleet issue ships.

The second echelon of resupply consists of the primary stock points in CONUS, with other air activities that stock limited items of aviation material. In some cases, which could include external aircraft fuel tanks, the second echelon of resupply might be a manufacturing or industrial distribution activity.

b. Movement

The distribution of external aircraft fuel tanks to the operational squadrons, whether shore-based or sea-based, requires the physical movement of these items, starting with the manufacturer and proceeding through the three echelons of supply. The modes of transport will differ between the various supply points (Figure 10, Section IV.B). For each mode of transport, there will be alternating

requirements for packaging, crating, containerizing, and materials handling. These requirements will also differ, depending on whether the external fuel tanks are completely assembled or nested.

c. Storage

Storage space aboard aircraft carriers and cargo ships is a critical commodity. Aboard carriers, spare external fuel tanks are either stored between deck stringers in the ceiling of the hangar bay or dead hung on downed aircraft. Aboard cargo ships, the tanks are in skeletal crates to be stacked in holds or lashed topside. Even at Naval air stations, the tanks are dead hung on downed aircraft or stored outside in single layer wooden racks. Because of the lack of adequate storage space on aircraft carriers, there are very few spare tanks aboard. Thus, if cost were not a factor, the non-jettison doctrine (in effect today) would still be implemented because of the unavailability of replacement tanks.

Nestable tanks would help to alleviate this problem. They would be delivered in sealed containers that could be stacked so that many spare, unassembled fuel tanks could be stored aboard ship, especially if nesting ratios of 8 to 10 could be achieved. Also, an additional number of assembled tanks could also be stored, as is done today, without occupying any usable space.

d. Acquisition

Experience has shown that for external aircraft fuel tanks, government furnished equipment (GFE) is less costly and more reliable than contractor furnished equipment (CFE). A logical approach to acquiring new nestable external fuel tanks would involve an independent contractor, under government scrutiny, designing and testing a new tank. The next step would allow open competition for the large scale production of these tanks. Because of the

disposability requirement for the nestable tanks, any cost reduction measures that result from the open competition would represent critical award factors, as long as these measures would not degrade the integrity of the fuel tank design. During the design of the fuel tank, an integrated logistics support (ILS) plan should also be generated.

4. Conclusions and Recommendations

a. Conclusions

The principal conclusions that can be drawn from this survey are as follows:

- The development of disposable, nestable external aircraft fuel tanks for Navy carrier operations is a feasible option for implementation within the next five to ten years.
- Commonality of these nestable fuel tanks may be possible for use on the F/A-18, A-4, A-6, and A-7 aircraft, but doubtful for the F-14 aircraft, at least within desirable tank size limitations.
- A three-piece axial fuel tank appears to be the most feasible option, although longitudinal "canoe-like" sections should also be investigated.
- Not all desired operational requirements can be met, so there will have to be tradeoffs among storage space on ship, assembly location, assembly rate, and cost.
- Automated assembly aboard ship, using robotic equipment, appears feasible. However, the degree of automation will depend on tradeoffs among assembly and storage space availability, personnel requirements, and cost.

b. Recommendations

The following two recommendations are presented as possible tasks for the second phase in the development plan for the distribution of disposable, nestable external aircraft fuel tanks:

- Task 1: Select a set of five feasible system design concepts to be considered as likely candidates for future disposable, nestable external aircraft fuel tanks. Perform a detailed preliminary design for each of the candidate system design concepts, considering both the fuel tank and the assembly/testing equipment.

- Task 2: Conduct a cost-benefit analysis evaluating the alternative system design concepts under different physical distribution concepts. This task will require the development of a simulation and methodology to generate the cost-benefit factors for a broad spectrum of distribution scenarios, which consider such factors as force size, geography, intensity of operations, and methods of resupply.

II DESIGN REQUIREMENTS

The development of a disposable, nestable, external fuel tank for Navy fighter/attack aircraft should satisfy a number of design requirements that will enable the aircraft to maintain their tactical range and mission endurance, especially in periods of protracted combat. These requirements are segregated under five major headings: functionality, durability, disposability, storability, and safety. The stated requirements are a synopsis of those specified in References 1 - 6.

A. Functionality

The fuel tanks must be capable of providing auxiliary in-flight fuel to presently deployed and future planned Navy fighter/attack aircraft. Thus, it is desired that they be compatible with the F/A-18 and F-14 aircraft, as well as the aircraft (A-4, A-6, A-7) employing the AERO1D fuel tank, through use of adapter plates or some other mechanism. However, the F-14 aircraft presents a unique problem from the other aircraft in that auxiliary fuel tanks are mounted on the engine nacelles and this configuration may not be susceptible to adaptation for use of a standardized tank. The present F/A-18 external tanks hold about 330 gallons of fuel, while the AERO1D tanks hold about 300 gallons. Thus, any new tank should have a capacity in the 300 to 400 gallon range.

The fuel tanks must be aerodynamically sound so as not to significantly degrade aircraft performance from that of existing external fuel tanks. The fuel tank weight should not exceed the present tank weights by more than ten percent. The AERO1D tank, when empty, weighs around 150 to 200 lbs, while the empty F/A-18 tank weighs between 200 and 250 lbs. Thus, the new tank should have an

empty weight no greater than around 275 lbs. However, for ease of handling, the goal is for a lighter weight tank.

The fuel tanks must also withstand the rigors of carrier operations and limited aircraft maneuverability while in flight. This implies that the mechanical joints must remain secure and leakproof under the axial loads of catapult launch as well as under the normal loads imposed by subsonic climb, cruise, and limited maneuvering. Since the tanks are disposable, they will not be subjected to the stresses attained during carrier arrest, except possibly under emergency conditions when empty.

B. Durability

The fuel tanks must withstand the severity of carrier operations over extended periods at sea. The tanks must maintain structural integrity at temperatures ranging from subzero to 100-plus, as well as equally full ranges of humidity and precipitation. They must also withstand rough handling, both in their nested shipping and storage configurations, and in their fully assembled configurations aboard ship. One specific requirement is that they survive drops from aircraft pylon heights (about 40 inches) when empty. It is also desired that they be low maintenance items with a minimal number of functional components (plumbing, valves, etc.). The design of such components should emphasize simplicity.

C. Disposability

The fuel tanks must be capable of being jettisoned from the aircraft during flight. This requirement must apply to both empty tanks and to partially full tanks, the latter imposing the more stringent requirement. A partially full, malfunctioning external fuel tank poses several problems. First, it hinders the aircraft's maneuverability, which could be critical in combat operations.

Second, it presents a significant safety hazard on carrier arrestment, where fuel force could either blow out the front section of the fuel tank or rip the whole tank from the aircraft. In either case, the careening part of the tank across the carrier deck could harm both men and equipment, and the strewing of fuel across the deck would present an extreme fire hazard. Another critical problem in periods of intense combat operations is the added maintenance burden on the squadron, which would already be over-stressed. Thus, the new tanks must be capable of being jettisoned when partially full, as well as when empty.

The significant requirement of the new external fuel tanks over existing external fuel tanks is that they be considered as disposable. Although existing tanks are jettisonable, the current doctrine is to retain tanks and suffer the aerodynamic penalties. There are two main reasons behind this doctrine: high cost and limited availability. The AERO1D tank, used on A-4, A-6, and A-7 aircraft, as presently supplied by the Israeli Military Industry, costs about $4,600. Initially the F/A-18 tanks cost about $65,000 per tank, but this has recently been reduced to about $12,500. The F-14 tank costs about $70,000. At these costs, the tanks cannot be considered disposable. The cost of the new tanks should be less than $1,000 to meet the disposability criterion.

The cost factor also contributes to the low availability of external fuel tanks today. Another significant factor that contributes to low availability is the limited amount of storage area on aircraft carriers, combined with the low storage density of the existing assembled tanks. This latter factor is discussed in the next section.

D. Storability

The new fuel tanks must have a higher storage density than existing fuel tanks to make more spare tanks available aboard carriers where storage space is at a premium. Present tanks occupy about 90

cu. ft. each of storage space and cannot be stacked on top of one another unless they are crated (which takes up more space). The storage density will increase with the requirement that new tanks be nestable. An increase in storage density by a factor of 5 appears to be presently achievable, but the desire is to increase storage density by factors of 8 to 10.

Nestable tanks will require on-board assembly, either in the hangar bay, on the carrier deck, or possibly on a supply ship attached to the carrier task group. The tanks must be capable of being assembled rapidly, with a desired goal of one every six minutes in periods of protracted combat. Because of this time constraint, the section with the functional components should be pre-assembled at the supplier's facility. Such pre-assembly should also provide better reliability. However, this would tend to reduce nestability and would have to be accepted as a tradeoff.

The tanks, when assembled, must also be transportable by the maintenance personnel, as is presently done aboard ship. Thus, the 10 percent weight increase limitation (Section A) is also a materials handling requirement.

E. Safety

The new external fuel tanks should meet most of the safety requirements of existing external fuel tanks relative to storage and aircraft loading. If any sealants or glues are used, they must not radiate any toxic fumes. The tanks, when full, must resist rupture or shattering when impacted by small fragments from exploding ordnance, or when jettisoned onto the deck. An additional desired (though not yet required) capability is that the structure materials be non-flammable or be sufficiently coated by a non-flammable substance to withstand a 15-minute period of susceptibility to fire. Existing external fuel tanks do not have this desired capability. In addition, the tanks must withstand fuel afterburner temperatures from preceding aircraft awaiting launch.

III FABRICATION AND ASSEMBLY

A. Fabrication of Nestable Elements

1. Materials

In choosing the materials for the elements of the fuel tank, one must consider the following:

- Strength to withstand these stresses--
  - Catapult launch while the tank is full
  - Limited manuevering loads in subsonic flight
  - Drop from pylon height while full
- Low cost (less than $1000)
- Safety
  - No toxic fumes
  - Withstand fuel afterburner temperatures
- Weight
  - Not more than 10% heavier than current tanks
- Resistance to fuel --
  - Not susceptable to corrosion by JP-4 and JP-5.

An earlier study[5] considered several materials for a densely packed disposable external fuel tank using criteria such as these. This study considered steels, aluminum, titanium, plastics and composites. Steels were found to have poor strength-to-weight properties and also poor corrosion resistance. Aluminum was found to have good strength-to-weight characteristics and corrosion properties. However, it exhibits poor fire resistance. Titanium displays good properties all around but is extremely expensive and also requires special welding techniques. Plastics, such as PVC and CPVC, have acceptable strength-to-weight characteristics, but they would require

very thick walls. Such plastics also display poor fire resistance. Plastics typically used in composites, such as FRP epoxy and FRP vinylester, have better strength-to-weight characteristics than the above plastics (particularly when they contain reinforcing fibers) and exhibit good fire protection characteristics. The vinylester is fuel-resistant, while the epoxy is not.

Many external tanks in current use are made of aluminum. The structure is typically reinforced at the pylon mounting and has a skeletal frame. Aluminum has an advantage because there is much experience with its use in the aircraft industry. Consequently, there are many options for forming and joining aluminum components.

Such aluminum-skinned tanks do not appear to meet current and planned fire resistance requirements (MIL-T-18847C-not yet released). However, there are available fire resistant coatings (ablative or intumescent compounds) which may allow an aluminum tank to meet the required specification. Examples of such compounds are FLEXFRAM 805 (an intumescent compound) and FLEXFRAM 605 (an ablative compound), both manufactured by Fiber Materials Inc., Biddeford, MN, and FIREX RX-23773, an intumescent compound manufactured by Pfizer Corp., New York, NY. These compounds are all currently approved for Naval use. On the basis of manufacturer specifications, thicknesses of about 1/8" would be required to afford the necessary protection. Because the density of this material is less than half that of aluminum, such thicknesses seem reasonable. The material also provides additional wall strength.

An Air Force[7] study compared the fire protection capabilities of various intumescent and ablative compounds as well as a fire retardant insulating foam and heat reflective paint. The study found that the intumescent compounds did provide significant protection, while the ablative compound was less effective. In this study, however, these coatings were applied internally rather than on the outer shell, where they are bound to be most effective. The rigid foam also gave good protection, but was heavy and bulky. The reflective paint offered little protection.

Many current external fuel tank designs are based on composite structures that require no additional fire protection. The tanks are

constructed over a plastic or aluminum liner. The liner protects the composite from any corrosion due to the fuel and acts as a mandrel for winding the composite material. An effective and low cost method[8] has been developed for producing plastic liners by rotationally casting them. This approach is said to be superior to such methods as extrusion, because it allows the use of such materials as Celcon, cross-link polyethylene, and nylon. These are good liner materials that cannot be extruded. A common construction is two filament wound layers sandwiching a stiff insulating core[9,10,11], although such a core may not be necessary if a strong aluminum infrastructure is used[12]. One patented procedure fabricates filament wound aircraft fuel tanks[13]. Such tanks are extremely strong as they were designed to be "crashworthy", i.e., resistant to impact/ballistics, fire etc. Unfortunately, such a tank is too expensive to be disposable. These tanks typically cost more than $20K[10]. Such costs may decrease significantly if tank designs are standardized and produced in much larger quantities.

The above-mentioned composite tanks are constructed in one piece. If they are to be densely packed, then it may be desirable to assemble them from nestable elements. Cutting a preformed tank into nestable pieces is not sufficient because cutting through the filament greatly decreases the strength of the composite structure. If composites were to be used in a nestable tank design, then the individual elements would need to be made separately. While costs are prohibitive now for such a design, they would decrease substantially if tanks were manufactured in large numbers with just a few standard elements.

A low cost 300-gallon composite fuel tank with nestable elements has been developed.[14] The tank is made of plywrapped fiberglass reinforced plastic with an amine core epoxy liner. Aluminum bulkheads are used to provide stiffening. The fabrication procedure for the elements is described in detail in the referenced document.

2. Joining Mechanisms

In joining the elements of the fuel tank, the following must be considered:

- Strength to withstand the stresses named in the previous section.
- Sealing to prevent fuel leakage during catapult launch or limited flight maneuvers.
- A rapid assembly rate (i.e, one tank every 6 minutes).
- For safety purposes, the joining cannot involve any adhesives or sealants that emit toxic fumes.

To estimate the required joint strength (stresses that a joint between two nestable elements might receive during takeoff and flight), an analysis was performed. This analysis was based on a commonly proposed nestable element tank configuration. The configuration was that of a short cylindrical midsection (attached to the pylon) with a semi-ellipsoidal nose cone of circular cross section and a conical tail cone. The assumed static pressure within the tank is 100 psia (as per military specifications for the maximum allowable static pressure). The lengths of the nose and tail sections and the tank diameter were varied parametrically. The calculations were done for 1g loadings in both the longitudinal and transverse directions. There is a linear relationship between the number of gs and the hoop stresses. To find the stresses for a given loading, one needs only to multiply these results by that loading. The results are shown in Figure 1. Note that the stresses are given in units of lb per inch of seam length rather than psi, because the latter values depend on the wall thickness, while the former depend only on the tank diameter. Figure 2 presents the relationships for relating tank overhang lengths to tank fuel capacity, where overhang length refers to the length of either the nose section or tail section.

Typical parameters used in a tank design might be a diameter of 30 in, a nose length of 7 ft, and a tail length of 8 ft. Assuming that a catapult launch provides peak horizontal loadings of 6 gs and

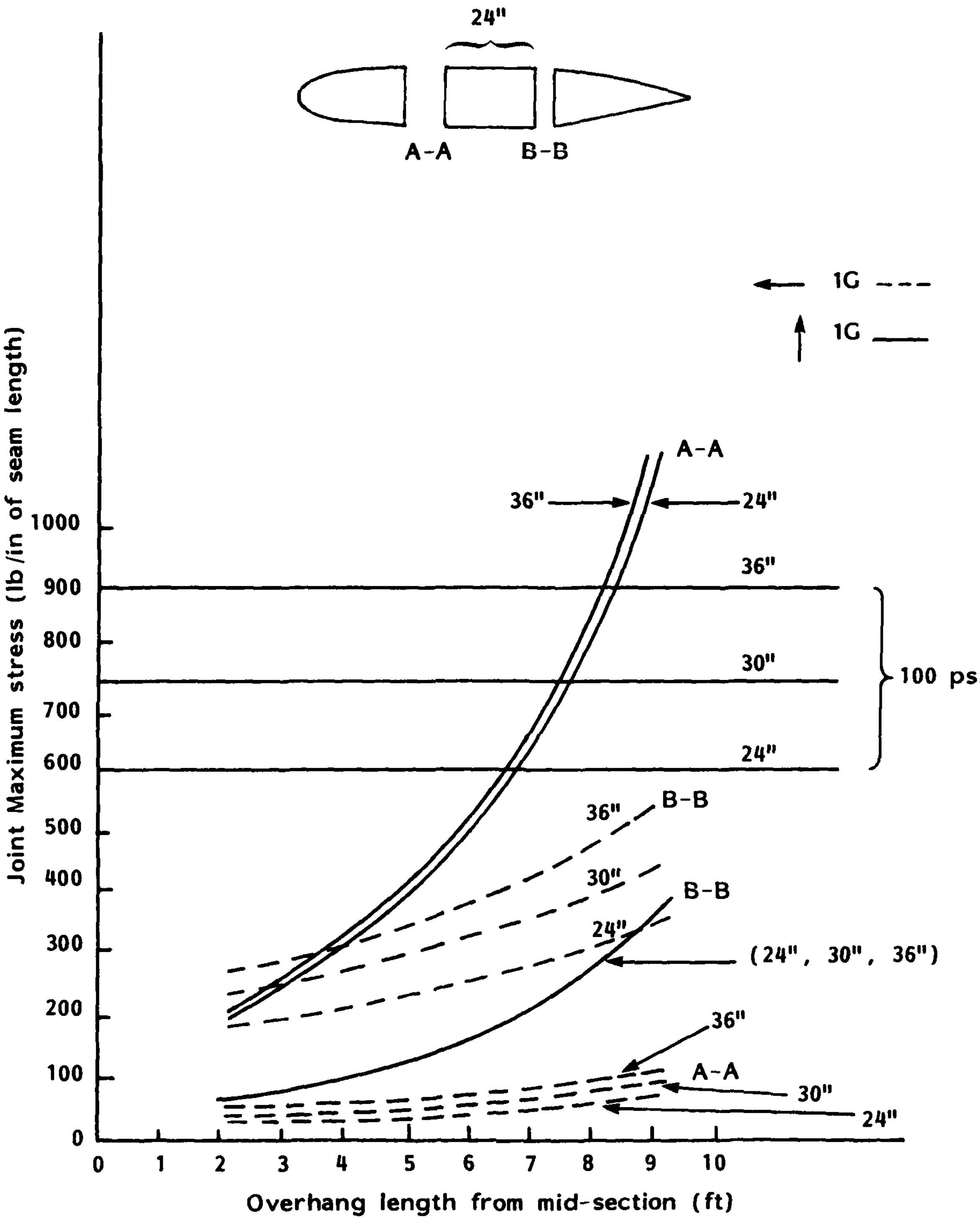


Figure 1 TANK HOOP STRESSES FOR VARIOUS ACCELERATING CONDITIONS AND TANK SIZES

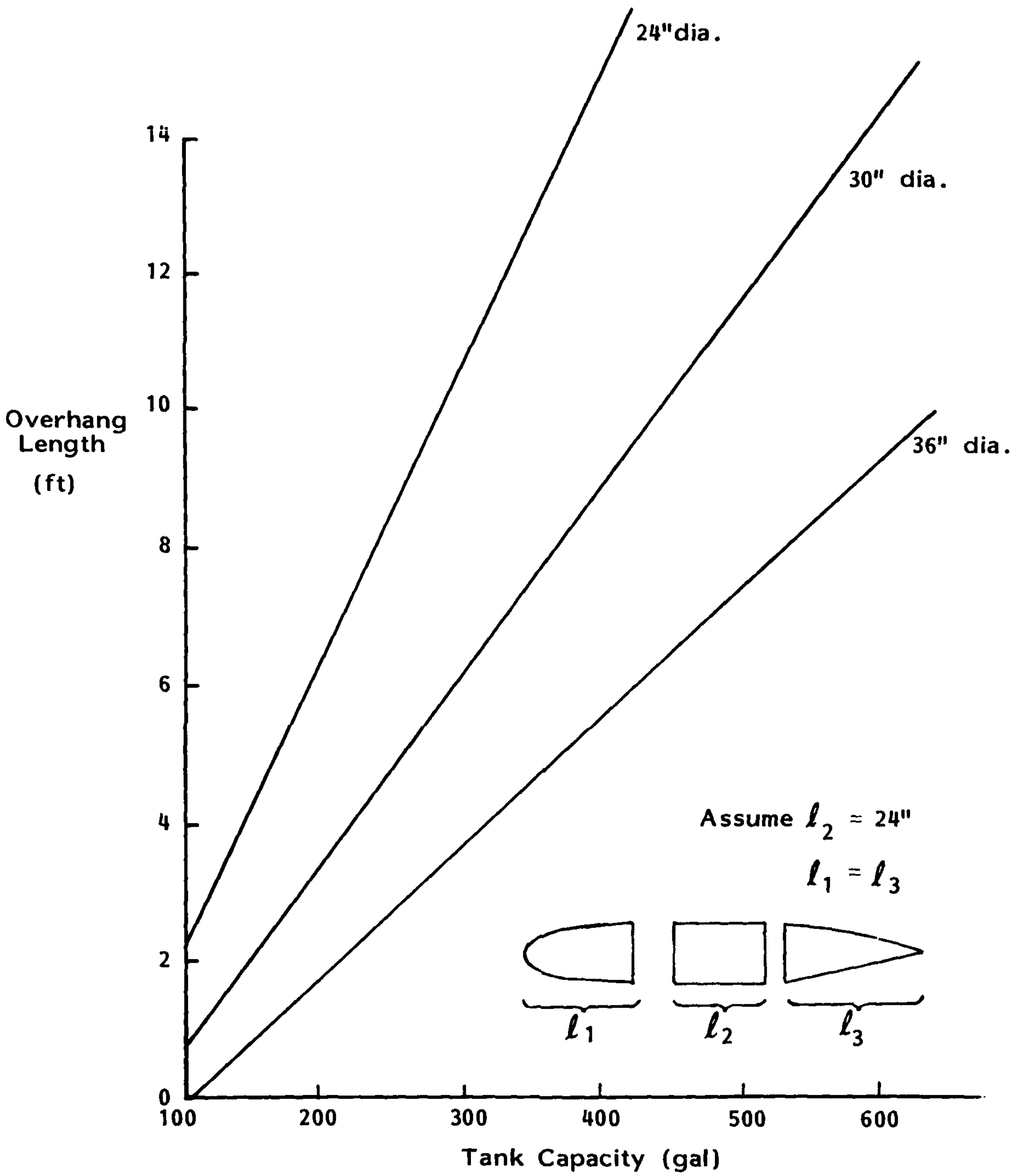


Figure 2 TANK LENGTHS REQUIRED FOR GIVEN FUEL CAPACITY

adding in the static pressure, we see that the peak stress at the nosejoint is about 1110 lb/in. At the tail, the peak stress is about 3150 lb/in. Such results aid in evaluating potential joining mechanisms.

If adhesives were used for the joining mechanism, then the nestable elements would likely be joined by a lap joint (each element overlapping a small distance into the other). This construction would transmit the joint stresses as shear stresses. If we assume that the elements were to overlap two inches, then the maximum hoop stress experienced, based on the above calculations, would be 1575 psi. This value is well within the limits of the typical strengths of many adhesives operating on aluminum or composites, especially acrylic adhesives.[15] Furthermore, the operating temperature range of such adhesives can approach 450 deg F, which is probably enough to withstand the exposure that a tank might receive directly behind a jet blast reflector while awaiting launch. Adhesives are also available that would not emit toxic fumes and could allow fairly rapid assembly.

The joining mechanism must not only provide the necessary structural strength, but it must also seal the fuel within the tank. One very effective method of sealing fuel tanks is based on using adhesives. One procedure[16] uses Scotchweld AF-10, manufactured by 3M Co., which has been used effectively on the integral fuel tanks of the F-102 and F-106 aircraft. The procedure (and perhaps the adhesive) would need to be modified to account for the specific geometry involved and reduce the assembly time. If composites are to be joined, then the use of rivets with the adhesive (as is proposed by this method) would have to be omitted.

An extensive survey was previously performed[17], focusing on various approaches to sealing integral fuel tanks. Some of the conclusions reached in that study may be useful for the problem of joining nestable elements of an external fuel tank. Approaches based on structural adhesives, such as the one described above, may be effective. An Air Force nestable tank design[14] recommends Dexter Hysol's EA934 as a suitable adhesive for field assembly of nestable elements made of plastic composite.

If the tank is made of composites, then the tank elements could be joined by winding a composite layer across two elements. There are some problems with this approach. If the composite is susceptible to rapid corrosion from the fuel, then some type of sealant must be used to protect the composite from direct contact. Probably such a procedure could not be accomplished within the time constraints imposed, although provisions for multiple assembly of tanks could alleviate this time constraint. Also, such a procedure would be likely to produce harmful fumes and may require a heat treatment procedure.

Some nestable composite tanks have been constructed by using clamps to hold together and seal the elements. The Air Force FILEX tank[14] uses an aluminum band circumferentially about the joint where the nose or tail fits on. While this joint failed a ballistic impact test, a stainless steel band and a stiffener ring around the inside of the joint could probably prevent such failure. Such a joint would have to be tested under operating conditions to insure that it could withstand a catapult shot.

If the material of the elements is aluminum, then there are some additional possibilities for joining mechanisms. Mechanical fasteners such as bolts or rivets can be used with sealants. One extensive survey[18] addressed factors affecting the quality of aircraft fuel tank seals.

Besides using mechanical fasteners, metallic tank elements could be welded together. Such a weld would probably be a fillet weld on a tightly fitting lap joint or a butt joint. Probably high quality welds could not be achieved with semi-skilled personnel in the specified time constraints, although current robotic welding systems, such as those produced by Newcore, Inc. should be able to meet this specification.

A novel welding technique has been developed for use with pressure vessels by NASA's Langley Research Center. In this technique, the sections to be welded overlap slightly. A strip of explosives is applied circumferentially around the inner surface of the inner piece. The explosives are detonated, forcing the inner wall into the outer wall with enough residual energy to fuse the pieces and

produce a metallurgically sound joint. Langley has demonstrated that this technique works well with aluminum up to .188 in thick. This thickness range includes the range expected for an external fuel tank made of aluminum. This technique is extremely simple, fast, and reliable. Also, almost no toxic fumes are released. One potential problem is finding an explosive that is considered safe for shipboard storage and use. However, the RDX explosive ribbon used at Langley is considered to be very safe from accidental detonation by any means.[19] Furthermore, the explosion would occur internally within the fuel tank, thus reducing its hazard to the external environment.

If an internal bladder is used to contain the fuel within the tank, then elaborate sealing mechanisms are not necessary. Tanks that use bladders or flexible gore are described in References 20 and 21. In fact, the latter describes a tank whose structure is based on a flexible gore with composite stiffeners. For a tank with an internal bladder, the nestable elements would still have to be joined in a structually sound manner. The tank's outer structure must support the loads that the bladder exerts on it under the extreme conditions of a catapult launch or limited flight maneuvers with a full, or partially full, tank. Anchoring the bladder to the walls of the tank would prevent it from shifting around within the tank. This may be done with adhesives or by using loops sewn onto the bladder.[12]

Most tank designs would also require a metal pylon mounting plate, or strongback, at the top of the midsection. The plate would distribute the stress at the point of attachment and provide a surface for the ejection foot to strike. If a composite structure were used, the plate might be overwound with filament or attached with an adhesive. An aluminum tank could fasten on the plate with adhesives, fasteners, and/or welding. In most designs, this step would already have been done in the fabrication of the individual elements to be assembled. Thus, there should be no time restriction on the mounting technique.

3. Geometry

The following criteria have implications for tank geometry:

(1) Standardization: the tank should fit the F/A-18, A-4, A-6, and A-7 aircraft (it would also be desirable, but unlikely,to fit the F-14 aircraft.

(2) Storage: the tank must be packagable for high density

(3) Capacity: the tank must hold from 200 to 400 gal of fuel.

A main concern of this project is to evaluate schemes for high density fuel tank storage, so a quantitative method was developed for describing storage density. The "packing factor" (PF) expresses the number of objects that could be stored in the space of one, i.e.,

$$PF = \frac{\text{volume required to store one object}}{\text{volume required to store an additional object}} \qquad (1)$$

If the object is one of several nestable elements that assemble into a fuel tank then the overall packing factor (OPF) may be expressed as

$$OPF = \frac{\text{volume required to store one tank}}{\text{volume required to store an additional tank}} \qquad (2)$$

$$OPF = \frac{\text{sum of (volume to store one of each individual element)}}{\text{sum of (volume to store one of each individual element/PF)}} \qquad (3)$$

The PF is valid only if there is a very large number of tanks stored in a space-efficient manner. If this is not the case, then a corrected packing factor (CPF) may be expressed as

$$CPF = \frac{N}{(n-1)/OPF + 1} \qquad (4)$$

where N is the number of tanks stored in the space-efficient manner. It should be noted here that the corrected packing factor is equivalent to the "nesting ratio" (the preferred definition used in the Navy) when the storage volume of a single nestable tank is the same as that of an assembled tank. The nesting ratio (NR) is defined as

$$NR = \frac{N \cdot V}{V_N} \tag{5}$$

where N = number of disassembled tanks in a container

V_N = minimum external volume of a container with N tanks in a disassembled state

V = minimum external volume of a crate containing one assembled tank.

To show this equivalence, Eq. (2) can be written as follows:

$$OPF = \frac{V}{\Delta V} \tag{6}$$

where V denotes the volume required to store one additional tank and V is as defined above. Substituting Eq. (6) into Eq. (4), we obtain the following:

$$CPF = \frac{N}{(N-1)/(V/\Delta V) + 1} \tag{7}$$

$$= \frac{N \cdot V/\Delta V}{N-1 + V/\Delta V} \tag{8}$$

$$= \frac{NV}{(N-1)\,\Delta V + V} = NR \tag{9}$$

since the denominator of Eq. (9) is simply the formula for computing V_N. However, if cross-nesting of different tank elements is possible, then the "V" term in the denominator would be less than the "V" term in the numerator, and the equivalence breaks down.

The overall packing factor is a more convenient indicator of nestability for comparing preliminary designs of alternative fuel

tanks since it is independent of the actual number of tanks to be nested.

For nestable fuel tank designs, where each component has the same maximum cross-section, the packing factor for each component can be reduced to consideration of only the dimension of length. As an example of how to use the packing factor expressions, consider a stack of ten nested nose cones. Suppose the length of a cone is 80 inches, and just 10 more inches are needed to store an additional cone in the stack. The PF is then

$$PF = \frac{80}{10} = 8.0 \tag{10}$$

but if we consider that the full space is required to store the first cone in each stack, then the CPF is

$$CPF = \frac{10}{(20-1)/8.0 + 1} = 4.7 \tag{11}$$

If the cones were to be stacked by tens, then this is the figure to be used to compute the OPF.

The packing factor (PF) concept can be used to evaluate proposed configurations for nesting elements. Several schemes were considered.

The USN Postgraduate School[2,3,5] has proposed a scheme in which the tank is composed of a long cylindrical midsection and short add-on nose and tail sections (see Figure 3). The ends of the midsection are sealed, as this element holds all the fuel. The advantage of this scheme is the simplicity of adding the nose and tail. The joints need not hold a large load or prevent the fuel from leaking. While specific dimensions are not available, some estimates of the dimensions (and, therefore, the PFs) may be made. If the tank midsection has a 30-in inner diameter, then it must be 11 ft long. The tail and nose sections are each assumed to be 3 ft long. Even if each of these three elements has a high PF, the OPF would be less than 2.0, because the PF of the midsection is 1.0 (it is not nestable), and the midsection makes up more than half of the total storage volume.

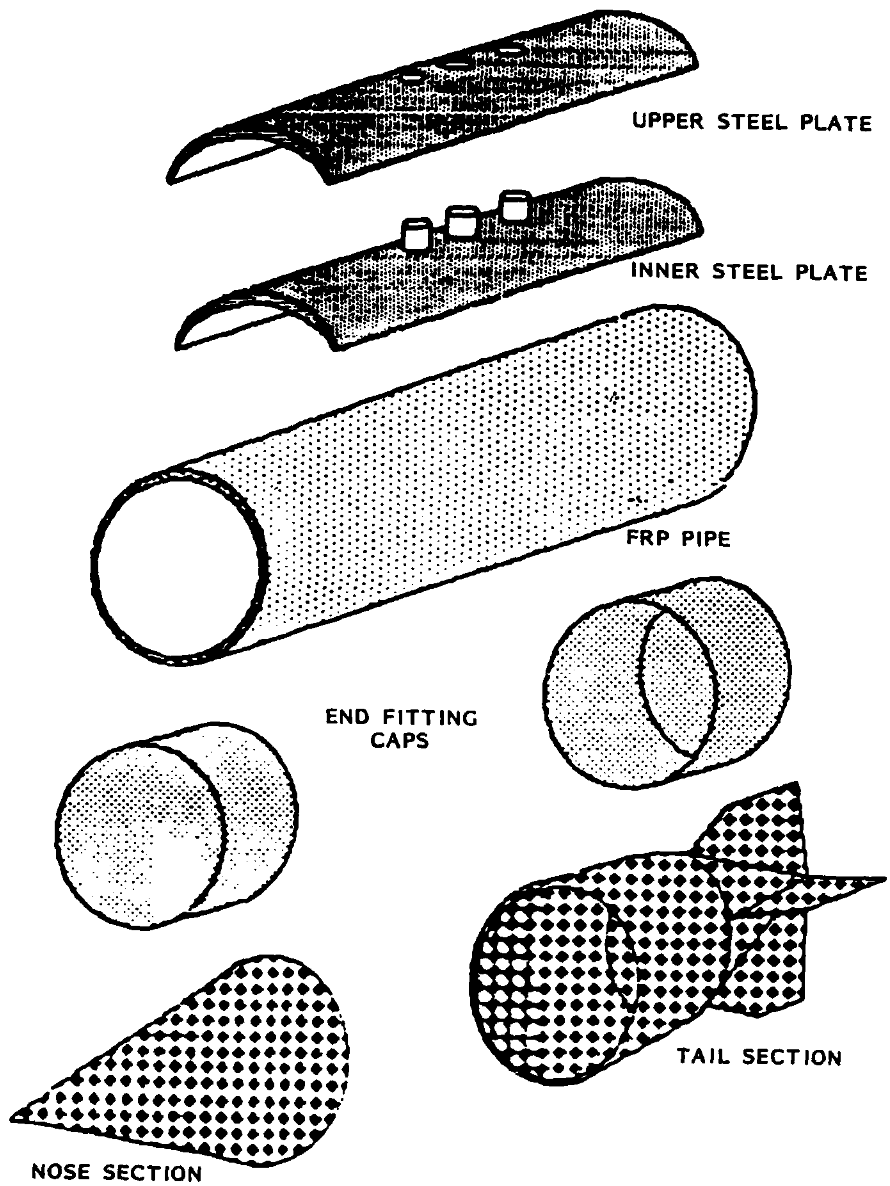


Figure 3 U.S. NAVAL POSTGRADUATE SCHOOL DISPOSABLE FUEL TANK CONCEPT

One commonly proposed nestable element scheme is similar to that proposed above, except that the nose and tail sections are longer, and the midsection is shorter (see Figure 4). The joints must hold a large structural load and seal in the fuel. By using dimensions from an existing 300-gallon external fuel tank (manufactured by Pastushin Industries Inc., Los Angeles, CA), estimates of the OPF can be made. The midsection that includes all the necessary plumbing and mounting fixtures, is assumed to be 36 in long. The outer diameter at the midsection is just over 30 in. The total wall thickness of the tank will be assumed to be 1/4 in. This thickness includes the tank structure and any necessary protective coatings. The nose element is a semi-ellipsoid with circular cross section, and the tail element may be approximated by a cone. The base of each is assumed to be 30 in outer diameter. The nose has a PF of 5.5 and the tail has a PF of 60.0. The midsection is not nestable and therefore has a PF of 1.0. The OPF is then computed as follows:

$$\mathrm{OPF} = \frac{(74 + 36 + 108)}{(74/5.5 + 36 + 108/60)} = 4.3 \tag{12}$$

This OPF, an improvement over the previous design, can be further improved by changing the shape of the nose to raise the PF. (Note that the PF for the conical tail was 60.0, while it was only 5.5 for the ellipsoidal nose). An OPF of about 5.0 is a reasonable expectation for this nesting scheme.

The packing factor of the above scheme has a major limitation: the midsection is not nestable. The Air Force has developed a nesting scheme similar to that above, except that the midsection is nestable (see Figure 5). The midsection has a single, longitudinal seam, and the pieces may nest up to four deep, similar to the way stovepipe is stored when the seam is opened. Adding this capability to the above scheme yields the following:

$$\mathrm{OPF} = \frac{(74 + 36 + 108)}{(74/5.5 + 36/4.0 + 108/60)} = 9.0 \tag{13}$$

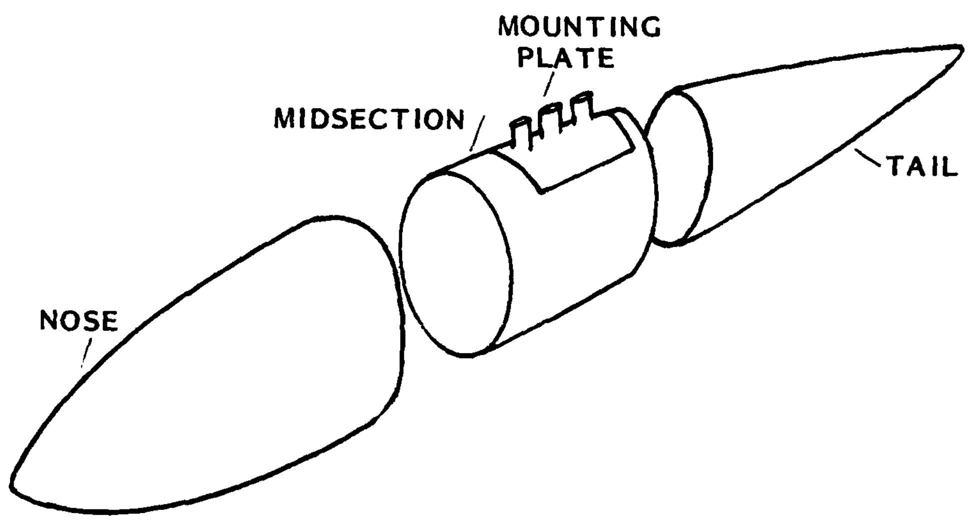


Figure 4 COMMON NESTABLE FUEL TANK CONFIGURATION

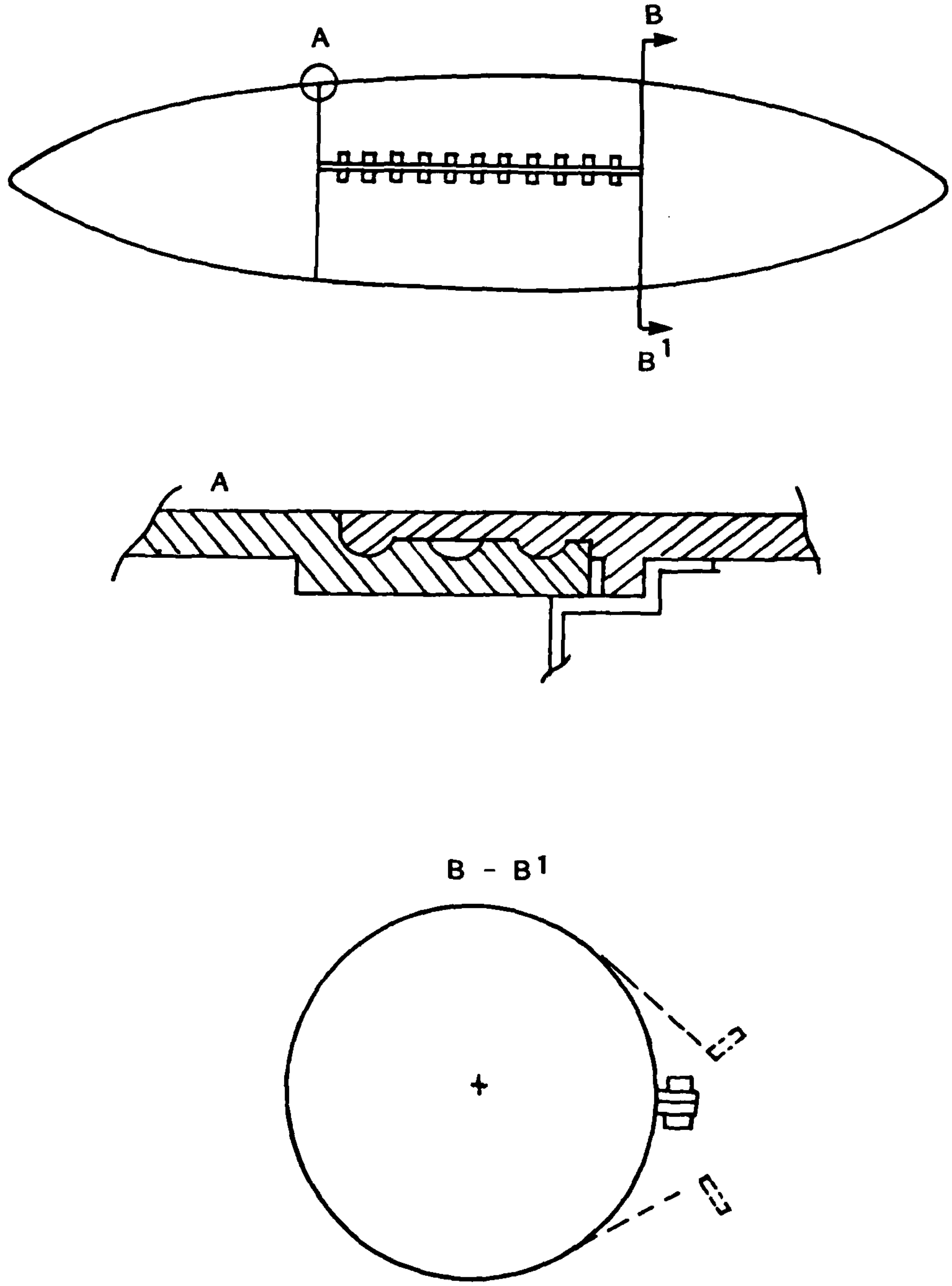


Figure 5 U.S. AIR FORCE NESTABLE FUEL TANK

Again, with improved nestability of the nose section, the OPF can be increased. For this case, an OPF of 15.0 certainly seems possible. This scheme requires the midsection material to flex to some degree. If this is not the case, then the midsection would need to be broken into two nestable half-cylinder elements. In this case, a PF of 6.0 for the midsection is possible for 1/4 in. walls. A drawback is that the nose and tail sections could only be joined with the midsection after its assembly. This restriction may cause the assembly time to exceed an acceptable limit.

Of course, the entire fuel tank could be split longitudinally (see Figure 6). As noted above, assuming 1/4-in walls and a 30-in OD gives an OPF of 6.0. A problem with schemes that involve midsection assembly is this: any internal plumbing could not be preassembled. Also, to achieve the 6.0 OPF, the pylon mounting plate or strongback would have to be joined to the tank at assembly time.

Another Air Force tank design is a hybrid of several of these nesting schemes[14]. This design features a long midsection (composed of two half shells) that holds all the fuel. A nose and tail section with fins are added to the midsection. This tank has a nesting ratio of 8, measured as the number of nested tanks compared to the number of assembled tanks that may be stored on a railroad car. In the nesting scheme, the nose and tail are stacked and surrounded by the half shells. The fins are stored flat.

If any tank design requires tail fins for proper aerodynamic performance, then the fins could be added to the tail section at assembly time so as not to interfere with the nestability of the tail section. The fins could be stored in flat sheets and attached to the tail in a manner similar to high quality darts.

Aerodynamic considerations demand smallness in the front profile area of the tank. Most present designs have circular or elliptical cross sections that are about 30 in wide. By referring back to Figure 2, such a restriction means that a 400-gal tank would have to be about 19 ft long and roughly centered about the mounting point on the wing. For a 300-gal tank, the length would be about 14 ft, while a length of 9 ft would suffice for a 200-gal tank. Using the same tank design on

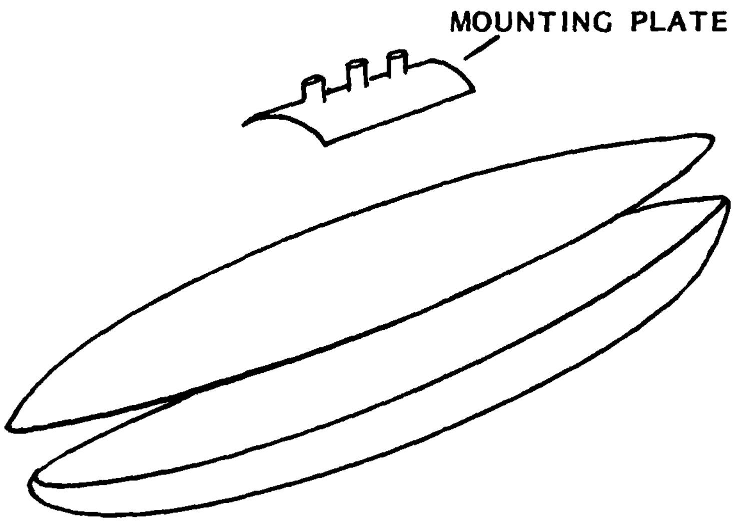


Figure 6 ALTERNATIVE NESTABLE FUEL TANK CONFIGURATION

all aircraft would be cost-effective. Specifications of the aircraft in question (F/A-18, A-4, A-6, A-7 and possibly F-14) will require further research.

If complete tank standardization is not possible, there still may be advantages to breaking up the tank into nestable elements. For example, the mid-section of the tank could be different for different aircraft, while the nose and tail could be identical.

4. Internal/External Plumbing

The following criteria apply to concerns with the internal and external plumbing required for the fuel tank:

- Standardization: the tank should fit the F/A-18, A-4, A-6, and A-7 aircraft (also desirable to fit the F-14)
- Pumping logistics: the tank must be fitted for an input pressurization port and an output port that can deliver fuel to the main aircraft tanks, regardless of the amount of fuel in the tank, in a manner compatible with the aircraft fuel system operation.

The fuel tanks would require only two fluid ports and possibly no electrical connections. Through the first port, pressurized air would be pumped, allowing fuel to be drawn through the second port. These external fuel tanks would dump their fuel into the main tanks of the aircraft (rather than into engines), so the flow rate would not need to be carefully regulated (only within a specified range), and the amount of fuel in the tanks would not need to be known. The needed flow could be provided through the output port by a pickup tube extending to the lowest point of the tank.

The required plumbing is not a difficult design issue. There are some points of caution, however. If the tank is manufactured out of a composite material without consideration of port locations, it is not

permissible to drill the necessary holes and insert the fittings. This would interrupt the filament windings in the composite structure. However, if consideration for port location is made at winding time, doilies may be placed at the desired port locations which will provide reinforcement for subsesquent hole drilling. If an internal bladder contains the fuel, then the material at the fittings would need reinforcing to prevent ripping during high g loadings.

Plumbing standardization may not be as difficult an issue as presently assumed. That is, the ports could be connected to an adapter plate, which would also allow the tanks to be mounted to several different types of aircraft. From there, the ports could be connected to the aircraft's fuel system in any way desired. The adapter plate need not be jettisoned during flight and, therefore, the breakaway feature of the fuel lines could be handled there. The manner by which the adapter plate remains attached to the aircraft, however, does present a design challenge. If all the connections were located near the mounting pylon in this manner, the connections could also be shielded from possible exposure to high temperatures from fire or jet blast.

An attractive safety feature would be pressurization of the fuel tanks with an inert gas such as nitrogen (rather than air) to help prevent the chance of the fuel within the tank igniting. Several research projects have revealed the effectiveness of this approach.[22,23,24] However, implementation of this feature would probably require some retrofits for existing aircraft, which may not be an acceptable option.

5. Inspection

The shipboard tank assembly must be done under rigid time constraints and may be performed by automated machinery, or even possibly by unskilled seamen, especially during protracted combat operations. Thus, proper fabrication of the elements is important. The dimensions must match closely at the mating surfaces. Also, the

joining mechanism would need clean mating surfaces. Protective wrapping of the mating surfaces may be advisable.

In tank designs where a protective fire coating is applied to the nestable elements at production time, this coating must not be damaged. Again, a protective wrapping around such elements may be advisable. Such wrapping may go between the elements when they are stored in a stack.

The Air Force has looked into quality control in both composite materials and adhesives and sealants[25]. They have developed semi-automated test procedures for composites (PASS) and adhesives and sealants (PARIS). Such tests may be useful in the production and field assembly of nestable fuel tanks.

B. Assembly of Fuel Tanks

1. Robotic Equipment

The assembly and testing of the fuel tank would take place in a specialized machine. For a nesting scheme consisting of two or more axially sliced sections, this machine would hold two parts to be joined, align them, and move them together as required. This machine must also be able to rotate either or both parts so that the forming or welding tool could reach the entire seam. An alternative would allow moving of the tool around the circumference of the tank parts. The machine would also have a head that mated to the tank support so that the tank could be pneumatically tested after fabrication. This assembly/testing machine would be about the same in size and weight, whatever the method of joining -- welding, adhesive joining, or explosive joining.

The assembly/testing machine would consist of a pair of rings into which the tank parts were inserted axially. These rings would grip the tank circumference uniformly (as by pneumatic inflation of a contacting bladder or by extension of many large, low pressure pads). The gripping rings then would turn the parts past the joining tool,

whether that was a welding head or an adhesive applicator. The assembly/testing machine would weigh about 1000 to 2000 pounds and would handle the tanks horizontally. However, the assembly could be done as easily if the machine were oriented vertically. The machine could be mounted between the tank part supply and the hangar deck. For example, the machine could be permanently located on a bulkhead from a storage room. The fixture could also be portable and stowable.

Robotic equipment is better suited to some parts of the fuel tank assembly procedure than others. There are six steps in the procedure:

(1) Obtain a fore, aft, and center tank section.
(2) Prepare the shells for mating.
(3) Mate the shells (to each other or to a center section).
(4) Fasten the shells (together or to the center section).
(5) Functionally test the assembled tank.
(6) Deliver the finished tank.

The methods of storing, joining, testing, and delivering the shells must be carefully engineered to place the fewest demands on the automation equipment. Such engineering will lead to a more robust and reliable automatic system and will also make it easier for people to perform the task if the automation equipment is out of service.

Steps (1) and (2) are likely to be the most difficult, because they present the robot with more variability than the other steps do. Below, we itemize the task characteristics that increase or decrease the difficulty of each step for the robot.

a. Step 1 (Obtaining Tank Parts)

To obtain a set of tank parts, it is necessary to do the following:

(1) Locate the individual parts required.
(2) Remove them from storage.
(3) Transport them to the assembly area.

An important system decision concerns the grouping of tank parts at various stages in assembly. The following part groupings are important:

- Type and number of parts in a shippable group (e.g., a pallet of twelve stacks of nested tank halves).
- Type and number of parts in a storable group (e.g., a stack of ten nested front halves secured to a bulkhead).
- Type and number of parts (in a group) that may be brought to the assembly area (e.g., the robot might carry one tank half at a time from storage to the assembly area).
- Type and number of parts in local storage in the asembly area. This might be a stack of nested tank halves with protective covers. Or, the protective covers might be removed, and the tank halves might be separated, with each placed in a different individual rack in local storage.

Some important factors in making these system decisions are listed below:

- Space requirements
- Tooling requirements (e.g., racks, containers for removed protective material, grippers for carrying parts).
- Time to break down shippable packages (e.g., into storage packages, then into transportable packages).
- Costs (capital, maintenance, manpower, etc.)

Certain factors would make it more difficult for the robot to obtain tank parts:

- Lack of information about tank parts location.
- A part storage method restricting access to parts. (The worst way would be to store the parts casually, wherever there was any space available in the ship, in areas where

other equipment might also be stored and where people might be present).

- A long distance, or many obstructions, between the storage area and the assembly area.

Factors that would help the robot to obtain tank parts are noted here:

- Storage of the tank parts in special racks, in a dedicated area adjacent to the assembly area, protected against casual access by untrained ship's personnel.
- Automatic tank parts inventory. As a minimum, the required data could be entered manually by trained personnel. It would be better if the robot control system could directly verify the presence of all tank parts.
- Tank parts stored so that they require as few handling and preparation operations as possible.

b. Step 2 (Preparing Tank Parts for Mating)

Storing tank parts in condition to be mated may be impractical. For example, there are preparations to be made. The tanks may need special coatings or packing, the tank shell rims may need special covers, and a separating liner may be needed between nested tank halves to prevent them from sticking together or damaging one another. Any materials to be removed before mating the tank sections will make extra work for the robot. Any of these materials that are nonrigid (e.g., springs, straps, plastic film) and any small objects (screws, bolts, clips) will be very difficult for the robots to handle. Any packaging material to remove should be rigid and should be designed with appropriate handles for the robot to grasp. It would be advisable to design the packaging when the robot gripper is designed and when other related tooling is designed.

c. Step 3 (Mating Tank Parts)

Mating can be facilitated by the following:

- Designing the mating surfaces so that parts can be pushed together (not screwed, not turned).
- Providing generous chamfers on parts to reduce the accuracy required of robot motion to position the parts with respect to each other.
- Providing enough clearance and tolerance to make lubrication unnecessary between mating parts.
- Choosing mating parts materials that are not likely to seize or gall during mating.

d. Step 4 (Fastening Tank Parts Together)

- Choose a fastening method that minimizes preparation of the surfaces to be fastened.

e. Step 5 (Functional Testing)

- Test individual components before assembly.
- Test assembled tank.

f. Step 6 (Delivery of Tanks)

- Deliver tanks that have passed the functional test to a delivery station.
- Deliver tanks that have failed the functional test to a different station for disposal, rework, or scavenging.

Steps (3) through (6) are easier than steps (1) and (2) for two reasons:

- It may not be practical to produce a robot that can obtain fuel tank shells from casual storage areas. Insisting on using a mobile robot to fetch shells will only result in an inefficient, caged-off "robot run" that could better be replaced with conventional material transport equipment.
- It may not be practical for the robot to remove conventional packaging material from the fuel tank shells or shipping pallets.

Other recommendations:

- Where accurate manipulation is required, reduce the strength and power requirements on the robot arm by providing it with commercial handling equipment (e.g., a pneumatic load balancer).
- Reduce requirements for accurate manipulation in the vertical direction, because the robot arm must work against gravity.

2. Materials

Materials will depend on (1) the tank material selected, and (2) the method of joining to be used.

3. Personnel

A tradeoff exists between equipment complexity and human involvement. The driving force will be the requirement for a rapid assembly time. Although automatic equipment operation is the desired plan, a man would still be needed to set up and initialize the equipment and then monitor its operating performance. Initialization means verifying the tank part inventory, loading consumables (such as adhesive or welding torch or gas), verifying initial positions and

clearances, and coordinating with other aircraft maintenance and provisioning activities.

The assembled fuel tanks would be removed from the equipment manually and either taken to the aircraft for use or put in temporary storage. The crew performing this task would be the same crew that maintains the aircraft.

In case of a failure of the transport robot, personnel could unpack the parts and load them into the assembly/testing machine.

4. Maintenance

The equipment would require maintenance similar to that for other electrical-mechanical systems. After each run, parts of the equipment may need cleaning to prevent plugging or similar failure.

5. Inspection and Testing

The main inspection method would be the monitoring of the equipment behavior during assembly. Parts that resist sliding together, for example, suggest a rough-edge or other failure. Such a problem would be brought to the operator's attention. A complete and accurate automatic inspection is possible, but it would be much more cost effective to flag unusual behavior. Such flagging reduces equipment cost and allows the operator to take corrective action, possibly saving parts. We believe it is appropriate to call on human intelligence to solve the unpredictable events. The operator would decide the condition of the parts and decide how to proceed.

The main testing method would be done by pressurizing the tank to a rated pressure and then monitoring the holding of the pressure. This could be done automatically by the assembly/testing machine.

6. Aircraft Interface

The tanks would be taken manually from the assembly to the aircraft.

Different aircraft would require different attachment and plumbing details. This means that (at least) the central portion of the tank must be individualized for each aircraft (see III.A.4). Stowage and assembly planning would be needed if more than one kind of tank were being assembled for a mission.

C. Straw Man Design Concept

Figure 7 shows the floor plan of a straw man design concept for the tank assembly facility. The robotic equipment operates only within the region enclosed by the dotted line, and people must be excluded from this area whenever the robots move. To guarantee this condition, adequate safety mechanisms must be provided around this region. Component parts arrive from the left on shipping pallets, and completed tanks are delivered at the upper right. The facility consists of the following stations:

(1) Tank end section pallet
(2) Tank center section pallet
(3) Assemblyl/test supply pallet
(4) Tank section de-stacking area
(5) Unstacked tank section area
(6) Separator ring disposal area
(7) Automatic assembly and testing machine
(8) Completed tank storage rack
(9) Defective tank storage rack.

Parts flow through the facility as follows:

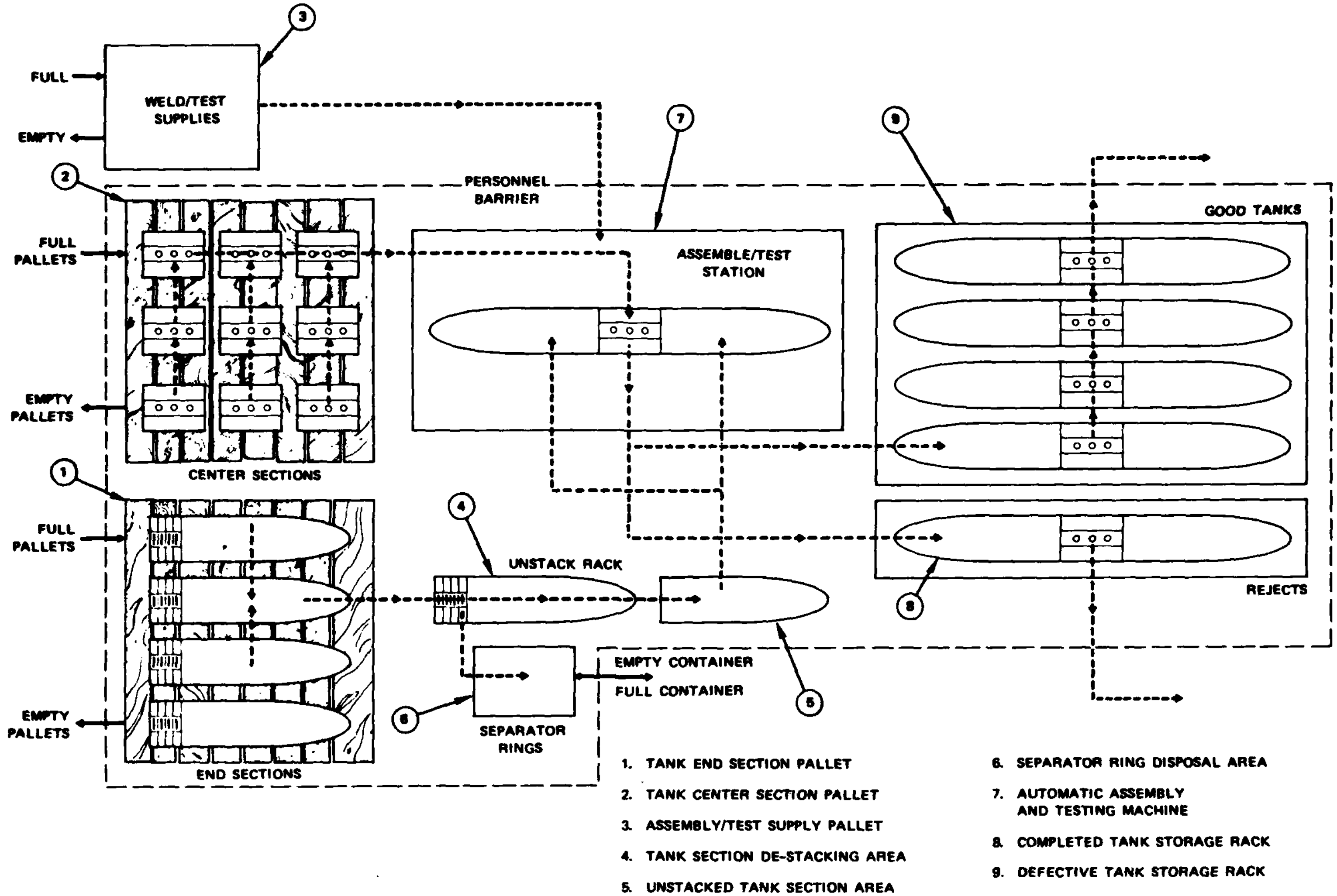
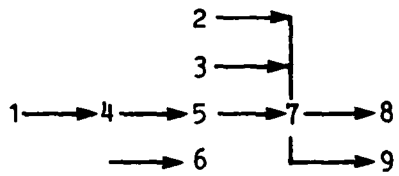


FIGURE 7 AUTOMATED FUEL TANK ASSEMBLY AREA (ROBOT NOT SHOWN)



The following sub-sections describe each of these stations in detail.

1. Tank Section Pallet

End sections are shipped in stacks, with several stacks laid side-by-side horizontally and in the same orientation on a shipping pallet. The crew inspects the end sections and removes any defective ones from the pallet. It is not necessary to deliver a full pallet of end sections to the robot: its sensors tell it how many end sections are present and where they are on the pallet. When the robot removes the last end section, it requests another pallet. This asynchronous, "demand-driven" method of operation makes it unnecessary to deliver complete "kits" (e.g., 2N end sections and N center sections). The robot merely takes end and center sections from their respective pallets as needed, and the crew replaces a pallet whenever it becomes empty.

Pallet supply can also be automated, though we have not assumed this in the present design concept. Removing conventional packaging material from the shipping pallet would be difficult for a robot. In this concept, we assume that a fork lift delivers a fresh pallet to a point just outside Station 1. People at that station then remove all packing material, dunnage, etc. from the pallet. When the preceding pallet in the facility becomes empty, the facility computer signals the people to exchange it for the next pallet. This allows overlap of packaging material removal with processing of end sections on the preceding pallet. Exchange of pallets is a rapid and easy operation, aided by simple handling facilities such as a fork lift, air bearing pallet supports, or mechanical slides.

Packaging material and empty pallets are removed to the left. They could be carried away by the same system that delivers fresh pallets.

The pallets should be designed with simple wooden fixtures that hold the end sections in place after the packaging material is removed. The pallets should hold the end sections accurately enough for the robot arm to acquire them (e.g., within an inch of their nominal position and within five degrees of their nominal alignment.

2. Center Section Pallet

Center sections are supplied to Station 2 and processed in the same way as end sections at Station 1. Because the stations are adjacent, the same people could service both. Simple fixturing arrangements are required on these pallets.

3. Assembly/Test Supply Pallet

Consumables for the automated assembly/test station arrive at Station 3, possibly on pallets. All handling of this material and packaging is manual. The personnel at this station would probably require a higher skill rating than those at Stations 1 and 2, because they must know how to load fresh consumables into the assembly/test station and remove empty consumable containers. They should also be able to recognize malfunctions, defective consumable packaging, and other problems. Consumables might include welding electrode wire, flux, ink or paint, bar code labels, and helium canisters (for helium leak testing).

4. Tank Section De-Stacking Area

This station is a slanted rack that holds a stack of end sections with their closed ends downward. Stacks of end sections are supplied by the manufacturer. There are protective plastic separator rings between consecutive sections, and there is one extra ring on the open

end of the last section in the stack. Figure 8 shows one of these rings. Figure 9 shows a longitudinal cross section through a stack of end sections, illustrating how the separator rings keep the tank sections from touching each other. These separators prevent damage to the edge of each section.

The stack of end sections slides down the rack, under gravity, until the tabs on the ring that separates the lowest end section on the stack from the next higher one reach a limit stop in the rack. This places the lowest end section in position for the robot to grasp. The robot separates the lowest end section by grasping it and pulling it away along the axis of the stack to Station 5. If the end sections tend to stick together, the robot could twist them to break sticking friction. Alternatively, the rack could have air jets that blow air into the space between the sections, forcing them apart by pneumatic pressure. The separator ring might be designed to convey the air from a nozzle on the rack to that space.

Before acquiring each of the other end sections in the stack, the robot arm grasps the handle of the lowest separator ring and pulls it away along a normal to the axis of the stack. Because the ring is split, the two halves separate and allow the ring to come away. The robot then discards the ring in the refuse cart at Station 6.

Removing the ring allows the stack to slide down the rack under the influence of gravity until the next ring reaches the stop. This places the next end section in the same position so that the robot can grasp it.

5. Unstacked Tank Section Area

This station is merely a holding area. If there is sufficient room, the robot could rotate the end section 180 degrees around the vertical in preparation for placing it in the left half of the assembly/test station. Alternatively, the robot could rotate the section while transporting it to the assembly/test station.

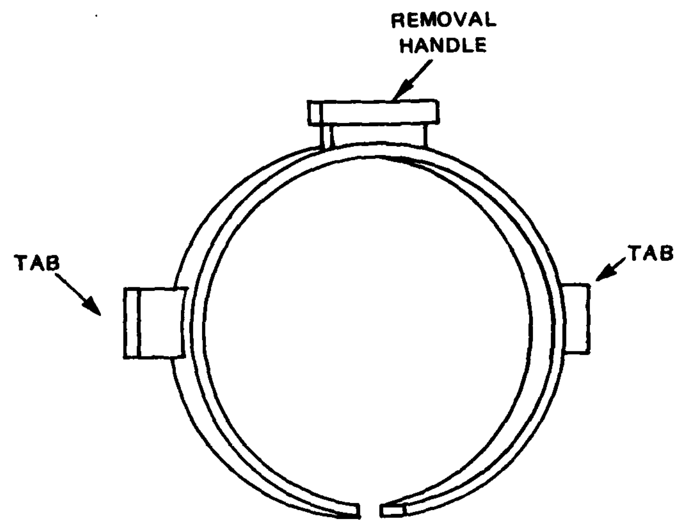


FIGURE 8 SEPARATOR RING

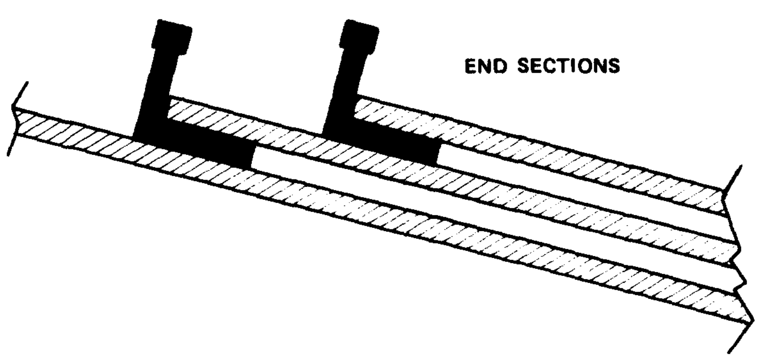


FIGURE 9 USE OF SEPARATOR RINGS TO PROTECT TANK EDGES

6. Separator Ring Disposal Area

This is a removable waste container, such as a wheeled cart. A person periodically removes this container when it becomes full of separator rings (or other material generated by the facility). There could be two of these stations, so that the robot could fill one while the other was being emptied and replaced.

7. Automatic Assembly and Testing Machine

This station is special-purpose, microprocessor-controlled, and automatic. It is designed to assemble a tank after the robot arm(s) load two end sections and a center section into it. This machine might test the individual components before assembling them, and it might request the robot arm(s) to replace any defective components. It functionally tests the assembled tank, and it informs the facility control computer of the results.

8. Completed Tank Storage Rack

Completed tanks that pass inspection are placed in this rack. The rack might hold more than one tank, as shown, providing compact tank storage in case of a short burst of high demand.

9. Defective Tank Storage Rack

Defective tanks assembled by the assembly/test station, as well as any defective tank components that were detected by the robotic equipment before assembly, come to this station for manual removal and subsequent repair, disposal or scavenging. This rack must be designed to hold a single end or center section or to hold assembled tank pieces that have come apart. The rack might hold more than one component or tank.

D. General Comments on Design Concept

Material flow is approximately unidirectional through the facility. This reduces congestion at entry and exit points.

Individual material flow paths do not cross. This simplifies material handling requirements (e.g., by allowing multiple robot arms to operate simultaneously along different paths for increased throughput).

Material flow paths are primarily horizontal, and vertical access is possible at all stations and along all paths. This allows use of gantry-style robot arms for improved lifting capacity for a given accuracy and/or cost. If properly designed, a single gantry robot arm could cover the entire facility without requiring any floor space. This design would be much simpler, much more reliable, and much cheaper than a mobile robot, if space constraints permit. A gantry design would also eliminate the need for separate lifting aids. Low ceilings will probably require a telecoping vertical arm section in the gantry. Such robots are commercially available, but further study of space constraints is required to determine whether any of the available sizes would be suitable.

Use of existing commercial equipment would be preferable to development of a new manipulator because existing equipment is cheaper, replacements would be easier to obtain, the manufacturer could provide skilled service, and competition would result in future price/performance increases.

The best choice of actuator (electric or hydraulic) for the robot joints will depend on shipboard constraints and commercial availability. Hydraulic actuators are strong, but they require complex pumping and valving equipment, and they leak oil. Electric actuators are often weaker, but they are much simpler to use.

An appropriate gripper for handling end sections might be constructed from the Baer brand of prehensile pneumatic fingers arranged along a strongback. The Navy uses such an arrangement to lift and handle torpedoes, so it should be able to carry these

aluminum tanks, which are much lighter. Experimentation with a prototype would be very useful.

Grippers for handling the center section and separator rings might have to be specially designed for those parts for maximum reliability. A simple parallel-jaw gripper might be adequate if those parts can be designed with suitable "handles."

Further automation of the supply and delivery operations on either side of the facility is possible. The main requirement is design of the shipping pallet for easy removal of packaging and dunnage by a robot. This would require further investigation.

Figure 7 is drawn for a nesting of four end sections per stack. Higher nestings are possible. An optimal choice would depend on detailed analysis of shipboard space constraints.

Simple sensors (e.g., contact switches) would meet most of the sensing needs in this facility, except for the assembly/test station.

The facility will require one computer that communicates with the operator and coordinates the activities of the other computers and equipment. This computer could probably also operate the robot arms, but it may be safer to use a different computer. The robot(s) themselves may have multiple embedded microprocessors for joint servo and gripper control. The assembly/test station will need at least one computer of its own (perhaps several) for real-time process control. The need will depend on the chosen methods of fastening and process control.

Processors of the 8-bit type may suffice for the simplest control functions, while 16-bit processors will probably be needed for the operator interface and robot arm control. The more complex process control functions in the assembly/test station may need a 16-bit processor, too. A 32-bit computer would be needed for initial software development and facility testing, but not for shipboard use.

Interfaces between pieces of equipment should be designed for easy upgrading, expansion, and application to other shipboard activities. Equipment should be modular, and standards should be established for interconnection of modules. Existing industrial or naval standards should be adopted. Existing standards are preferred to newly defined standards.

IV PHYSICAL DISTRIBUTION

The physical distribution of external fuel tanks for Navy fighter/attack aircraft complies with the standard procedures for the distribution of aviation peculiar items within the Navy supply system. The functions of physical distribution can be segregated under four major headings: inventory, movement, storage, and acquisition, which includes integrated logistics support (ILS).

A. Inventory

One version of the inventory management and storage policy for the Navy is described in Reference 26. The following discussion summarizes this policy as it pertains to aviation-peculiar material.

The item management and logistics responsibilities for Navy aviation material lie with the Aviation Supply Office (ASO) in Philadelphia, PA, which is an inventory control point (ICP) under the Naval Supply Systems Command (NAVSUP). Material procured by ASO is consigned to six Naval air stations in CONUS, which are designated as primary stock points. In addition, several other Naval air activities in CONUS stock a limited range of items. Items resupplied by ASO from these activities are transacted on a"push" basis, where requisitioning is not required and resupply levels are based on accumulation and analysis of transaction item reports (TIRs) under the Uniform Automated Data Processing System-Inventory Control Point (UICP). The UICP is a system through which ASO uses standard hardware, programs, and procedures to accomplish its basic functions of provisioning, technical support, cataloging, inventory control, purchasing, and financial control. In addition, these activities also support local customers on a "pull" basis, where items are requisitioned by the

consuming activity. The customers supported by these activities are mostly naval aviation shore activities.

Operational aircraft squadrons, on the other hand, are resupplied under the base level concept, where stocks are located at a number of naval air stations and overseas depots. Under this concept, the range and depth of material stocked are determined jointly by ASO and the appropriate Naval air commander. Items are maintained at the base level at the point of anticipated usage and are resupplied on a "pull" basis. This concept provides for reporting of TIR transactions, giving visibility to ASO, while enabling large users of aviation material to replenish their stocks as necessary.

There are three levels of inventory for Naval aviation material: the organic level of supply, and two echelons of resupply. The aircraft squadrons draw supplies from the organic level. As necessary, the organic level requisitions additional supplies from the first echelon, which in turn, may requisition replenishment from the second echelon of supply.

Materials stocked at the organic level are specified in an Aviation Consolidated Allowance List (AVCAL) or other specially tailored support allowances. These materials are carried onboard ship for sea-based squadrons or are kept at the shore station for shore-based squadrons. The AVCAL lists the components, repair parts, and consumable items required for a ship or shore activity to perform its operational mission supporting assigned aircraft, with consideration for available organic repair capability. The AVCAL includes the items and quantities that should be on- board to achieve a self-supporting capability for a prescribed period. The AVCALs are based on analyses of aircraft and associated system requirements derived from such factors as deployment duration, anticipated aircraft use, and maintenance factors. Whenever special operations are anticipated, the AVCAL is either augmented or replaced by a special allowance list.

The first echelon of resupply for sea-based aircraft squadrons is usually the associated shore-based activity assigned under the base level concept. Fleet issue ships (either accompaning a task force or serving as members of the mobile logistic support force (MLSF)), do

not normally carry aviation peculiar material. However, in special deployments, these ships might carry this material, including external fuel tanks. In this case, the first echelon of resupply would be the fleet issue ships.

The second echelon of resupply consists of the primary ASO stock points in CONUS, with the other air activities that stock limited items of aviation material. In some cases, which could include external aircraft fuel tanks, the second echelon of resupply might be a manufacturing or industrial distribution activity.

B. Movement

The distribution of external aircraft fuel tanks to the operational squadrons, whether shore-based or sea-based, requires the physical movement of these items, starting with the manufacturer and proceeding through the three echelons of supply. The modes of transport will differ between the various supply points. For each mode of transport, there will be alternating requirements for packaging, crating, containerization, and materials handling. These requirements will also differ, depending on whether the external fuel tanks are completely assembled or nested. Figure 10 indicates the likely transport modes that could move the external fuel tanks from one supply point to another.

The first distribution of the external fuel tanks from the manufacturer will be either to a primary stock point with subsequent delivery to a base level stock point or directly to a base level stock point. The main transport modes will be merchant ship, rail, and/or truck. Fuel tanks manufactured in the U.S. will probably be shipped by rail and then by truck. Those manufactured overseas, such as the present AERO1D tanks in Israel, will be sealifted by merchant ships to CONUS, and then shipped by rail and/or truck to the appropriate stock point. Distribution from the primary stock point to the base level stock point will also be by rail and/or truck. Although deliveries could be made by air cargo or airlift by the Military Airlift Command

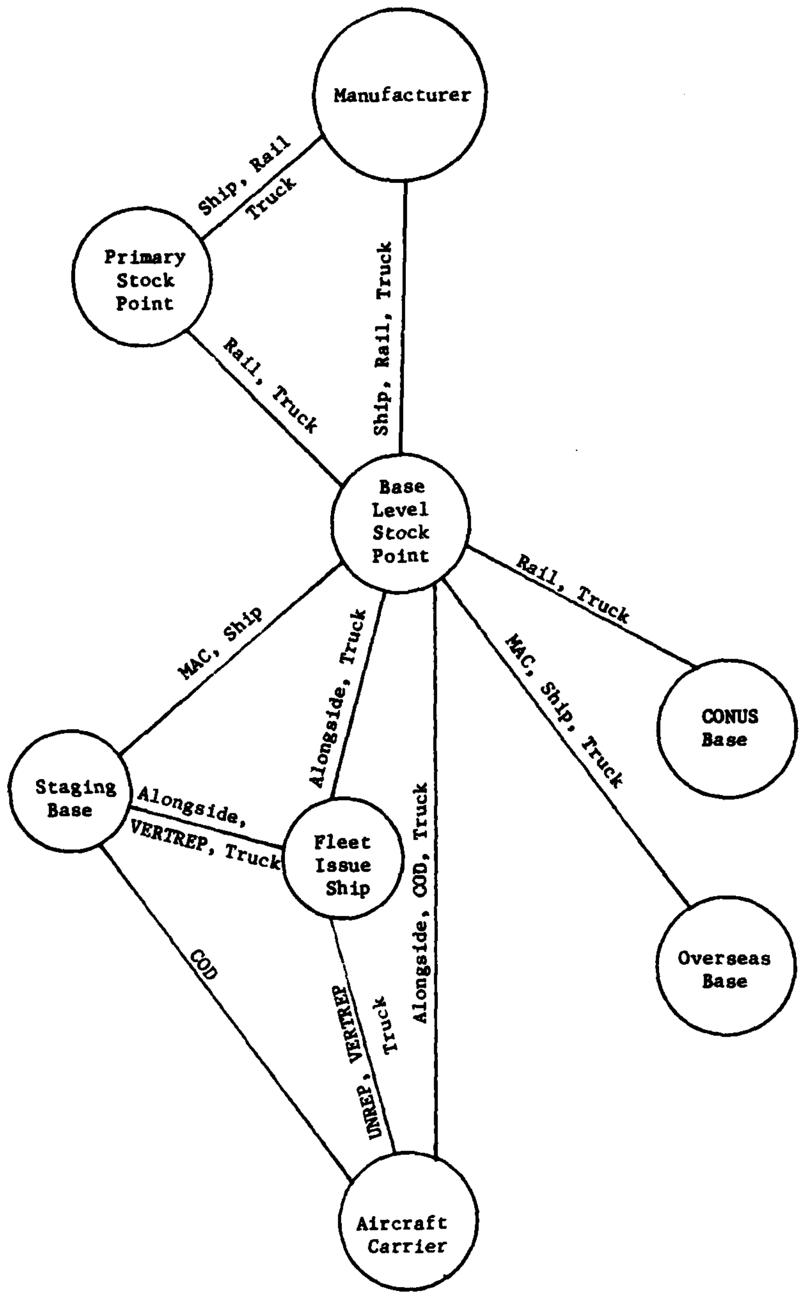


Figure 10 LIKELY TRANSPORT MODES BETWEEN VARIOUS SUPPLY POINTS

(MAC), this would be unlikely except in critical situations. The external fuel tanks, even when nested, are quite bulky, and delivery by air would be fairly expensive. Initial supply or replenishment of external fuel tanks to the aircraft squadrons can be accomplished in several ways, depending on the location of the squadrons and the pre-planned supply method. If the squadrons are located at CONUS bases, then transport will most likely be by rail and/or truck. If the squadrons are land-based overseas, then shipment could be made by merchant ship to a nearby port and then by truck to the airbase, or shipment could also be by direct MAC airlift.

For carrier-based squadrons, there are numerous delivery options. Initial stocks from the base level stock point will be sent to the debarkation point by truck and loaded onto the carrier. In some cases, some initial stockage could be delivered by carrier on-board delivery (COD) aircraft. In some scenarios, the aircraft carriers will be serviced by an overseas staging base. Spare stocks of fuel tanks would then be prepositioned at these bases, delivered from the base level stock point by merchant ships, military sealift ships, or MAC aircraft. Direct supply of external fuel tanks from the staging base to the carrier would then be made by COD aircraft. In some special cases, fleet issue ships may be required to stock spare external fuel tanks for replenishment to carriers. When operating out of CONUS, the fuel tanks would be trucked from the base level supply point to the debarkation point and then loaded onto the fleet issue ship. If operating out of a staging base, the fleet issue ship could return to the staging base port to take on replenishment stocks, or it could be supplied by vertical replenishment (VERTREP) aircraft. Transfer of replenishment stocks from the fleet issue ship could then be made by alongside underway replenishment (UNREP) or by VERTREP aircraft.

The alternative transport modes indicated in the above discussion shows that the external aircraft fuel tanks will be subjected to a variety of harsh environments, vibrations, and impact forces during transportation and the associated materials handling activities. For completely assembled fuel tanks, the present packaging, crating, and

containerization generally ensure operable tanks on delivery to the aircraft squadrons. However, for shipping nestable fuel tanks in a nested configuration, more stringent requirements will have to be specified and adhered to. One requirement will be that the tanks be shipped in sealed containers. Sealed containers help prevent corrosion and the introduction of foreign particles that could cause assembly problems when close tolerances must be maintained to ensure leak-proof joints. Another requirement will be more stringent lashing and sealing specifications to ensure that the nested elements do not impinge on each other destructively. The design of the nestable fuel tank elements and the manner by which the elements nest in their shipping configuration must consider the hostile conditions and rough handling that occur during transport.

C. Storage

Storage space aboard aircraft carriers and cargo ships is a critical commodity. Aboard carriers, spare external fuel tanks are either stored between deck stringers in the ceiling of the hangar bay or dead hung on downed aircraft. Aboard cargo ships, the tanks are in skeletal crates to be stacked in holds or lashed topside. Even at Naval air stations, the tanks are dead hung on downed aircraft or stored outside in single layer wooden racks. Because of the lack of adequate storage space on aircraft carriers, there are very few spare tanks aboard. Thus, if cost were not a factor, the non-jettison doctrine (in effect today) would still be implemented because of the unavailability of replacement tanks.

Nestable tanks would help to alleviate this problem. They would be delivered in sealed containers that could be stacked so that many spare, unassembled fuel tanks could be stored aboard ship, especially if nesting ratios of 8 to 10 could be achieved. Also, an additional number of assembled tanks could also be stored, as is done today, without occupying any usable space.

Materials handling requirements should not be altered with the introduction of nestable tanks, either onboard the carrier or at Naval air stations. A forklift would be sufficient to handle the sealed containers. The weight requirement of not more than 10 percent of existing fuel tanks would mean that the assembled tanks could still be handled by two or three crewmen, as is presently done.

D. Acquisition

Experience has shown that for external aircraft fuel tanks, government furnished equipment (GFE) is less costly and more reliable than contractor furnished equipment (CFE). A logical approach to acquiring new nestable external fuel tanks would involve an independent contractor, under government scrutiny, designing and testing a new tank. The next step would allow open competition for the large scale production of these tanks. Because of the disposability requirement for the nestable tanks, any cost reduction measures that result from the open competition would represent critical award factors, as long as these measures would not degrade the integrity of the fuel tank design.

During the design of the fuel tank, an integrated logistics support (ILS) plan should also be generated. This should be based on a detailed logistics support analysis (LSA). If the nestable fuel tanks can be procured at a low cost (i.e., less than $1,000), then the maintainability of the fuel tanks may not be a significant problem. That is, replacement may be more cost-effective than repair. However, if robotic equipment is used for on-board assembly of the fuel tanks, then the maintainability of this equipment will be a significant ILS item. Another important item will be the shipping container. These containers would be fairly high cost items because of the stringent requirements that would be imposed on them. Hence, these containers should be recycled through the supply system. The LSA should make this determination and, as such, it should be an element in the ILS plan. Personnel and training requirements will also have to be addressed and included in the plan.

V CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The principal conclusions that can be drawn from this survey are as follows:

- The development of disposable, nestable external aircraft fuel tanks for Navy carrier operations is a feasible option for implementation within the next five to ten years.
- Commonality of these nestable fuel tanks may be possible for use on the F/A-18, A-4, A-6, and A-7 aircraft, but doubtful for the F-14 aircraft.
- A three-piece axial fuel tank appears to be the most feasible option, although longitudinal "canoe-like" sections should also be investigated because of their higher nesting ratio.
- Not all desired operational requirements can be met, so there will have to be tradeoffs among storage space on ship, assembly location, assembly rate, and cost.
- Automated assembly aboard ship using robotic equipment appears feasible. However, the degree of automation will depend on tradeoffs among assembly and storage space availability, personnel requirements, and cost.

B. Recommendations

The following two recommendations are presented as possible tasks for the second phase in the development plan for the distribution of disposable, nestable external aircraft fuel tanks:

Task 1 Candidate System Designs

Select a set of five feasible system design concepts to be considered as likely candidates for future external fuel tanks. Figure 11 presents the set of possible combinations, considering the four major factors of size, material, configuration, and joining method. Preferred combinations are identified by the accentuated node connections. For each of the five candidate system design concepts selected, perform a detailed preliminary design for both the fuel tank and the assembly/testing equipment. This preliminary design would address such factors such as assembly space and time requirements, storage requirements, structural integrity, fuel tank capacity, personnel requirements, and cost.

Task 2 Cost-Benefit Analysis

Conduct a cost-benefit analysis evaluating the alternative system design concepts under different physical distribution concepts. This task will require the development of a simulation and methodology to generate the cost-benefit factors for a broad spectrum of distribution scenarios, which consider such factors as force size, geography, intensity of operations, and methods of resupply.

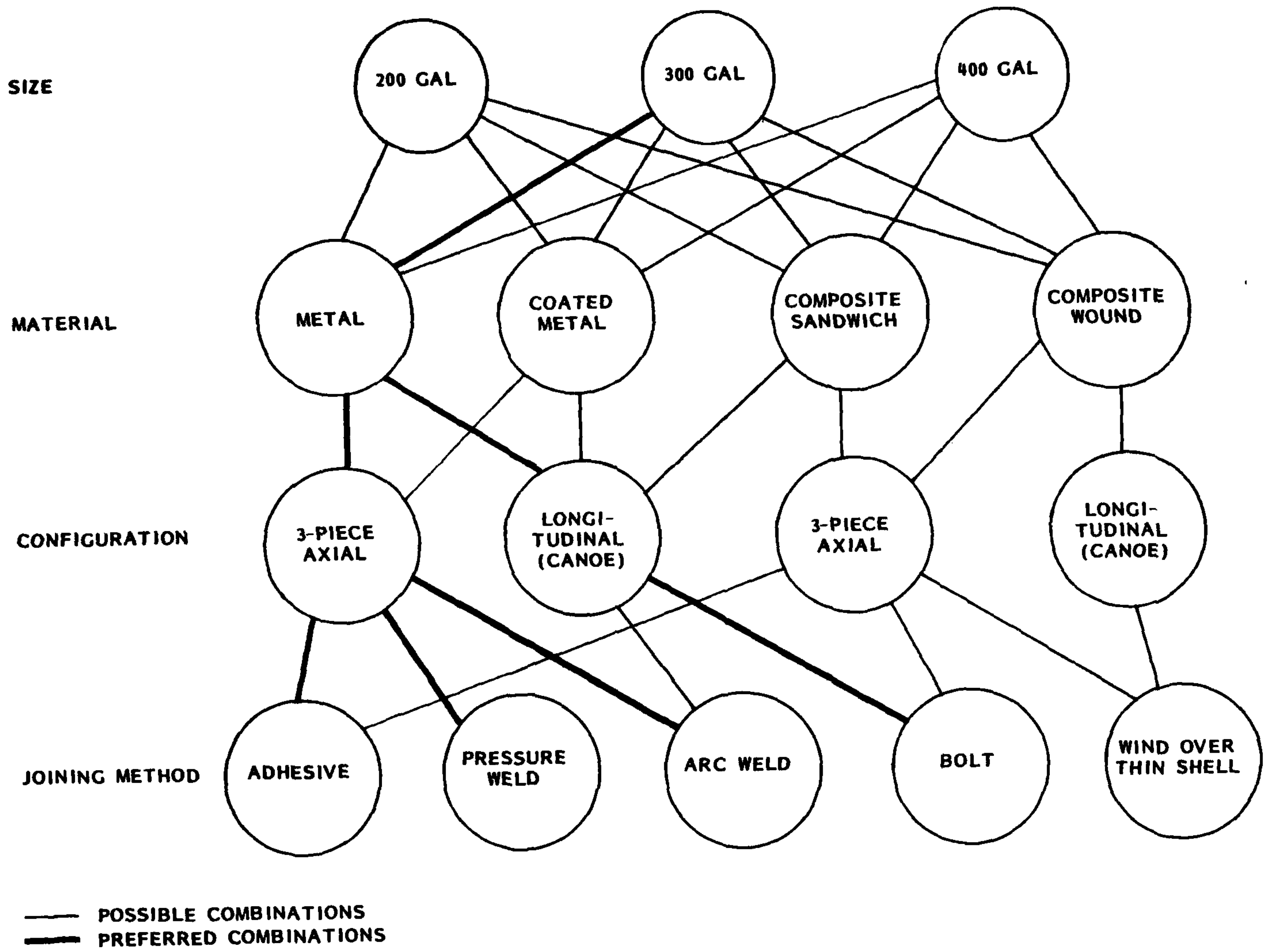


Figure 11 TANK COMBINATIONS

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